Materials for magnets & measurements - II

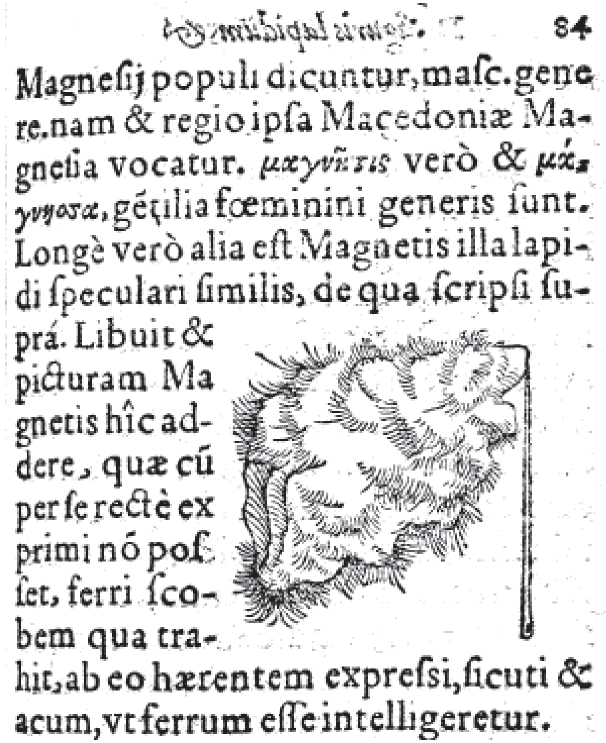
Lecture I, Mon Nov 27
- Introduction and bibliography
- Magnetic properties of materials: types of magnetic behaviour
- Families and behaviour of magnetic materials

Lecture II, Tue Nov 28
- Materials for magnets: structural, cryogenics, vacuum
- Non-magnetic materials, phase transformations and measurements
- Case study: a low permeability stainless steel for the CMS HG-CAL

CAS course on "Normal- and Superconducting Magnets", 19/11 – 02/12/2023, St. Pölten, Austria

Stefano Sgobba

But it is by far the magnet the most spectacular stone which I wrote about above. I am also pleased to add here a picture of a magnet, as by looking at the stone itself it could not be properly expressed the iron slag which she draws, sticking out of it, like if the needle would understand the iron to be there…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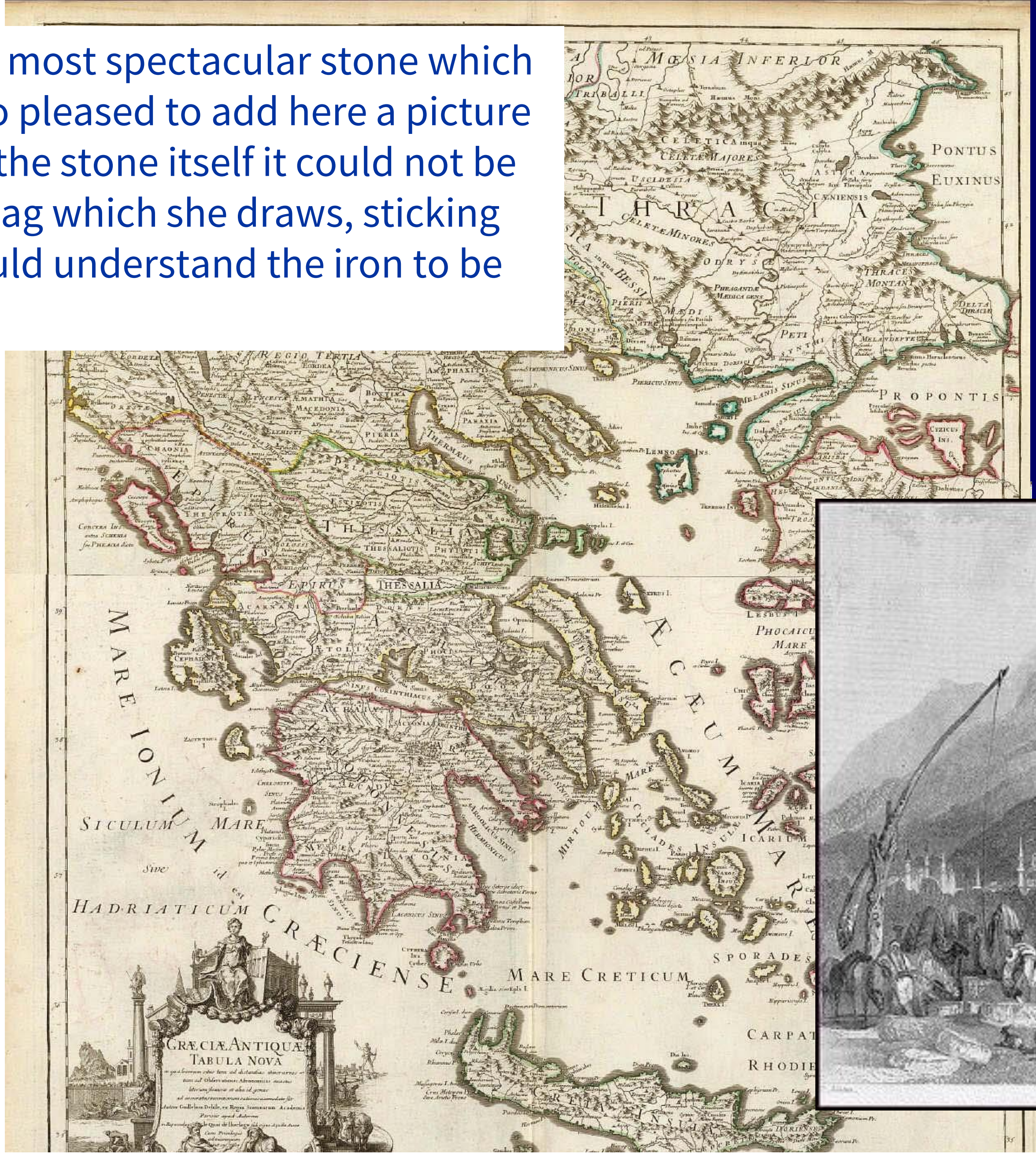
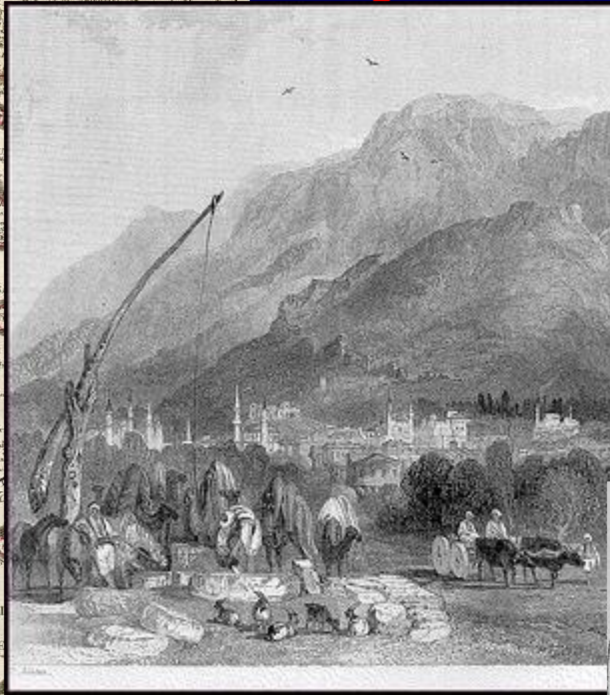
Magneſij populi dicuntur, maſc. genere. nam & regio ipſa Macedoniæ Magneſia vocatur. μαγνῆτις verò & μάγνησσα, gẽtilia fœminini generis ſunt. Longè verò alia eſt Magnetis illa lapidi ſpeculari ſimilis, de qua ſcripſi ſuprá. Libuit & picturam Magnetis hîc addere, quæ cũ per ſe rectè exprimi nõ poſſet, ferri ſcobem qua trahit, ab eo hærentem expreſsi, ſicuti & acum, vt ferrum eſſe intelligeretur.

Gesner, De omni rerum fossilium genere... (1565)





Magnes the shepherd, Pliny's Naturalis Historia, Book XXXVI, "The Natural History of Stones", chapter 25 – “The Magnet”:
Nicander is our authority that it was called Magnes from the man who first discovered it on Mount Ida and he is said to have found it when the nails of his shoes and the ferrule of his staff adhered to it, as he was pasturing his herds.

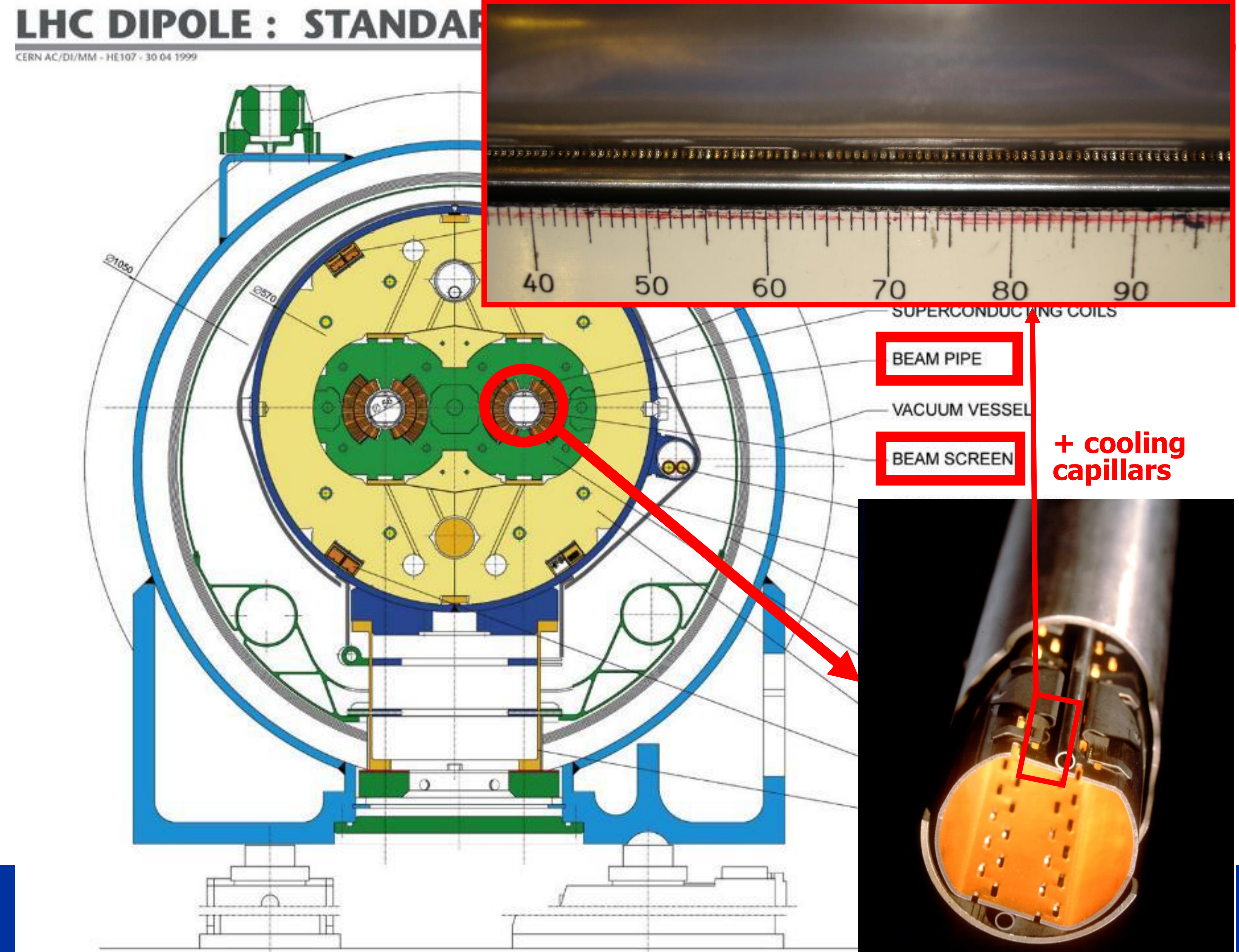
Types of magnetic behaviour, summary

Type | Material | At $T \cong 295$ K[a] | References and Comments

Type	Material	At $T \cong 295$ K[a]	At $T = 4.2$ K[a]	References and Comments
Diamagnetic	Cu	$\kappa = -9.3 \times 10^{-6}$	$\kappa = -9.4 \times 10^{-6}$	Fickett (1976); very pure Cu
	Nb	Paramagnetic	$\kappa = -1$	Superconductor below 9 K
Paramagnetic	Al	$\kappa = 2.0 \times 10^{-5}$	$\kappa = 2.5 \times 10^{-5}$	Fickett (1976)
	Ce	$\kappa = 1.6 \times 10^{-3}$	$\kappa = 23 \times 10^{-3}$	Edelstein (1968)
	Potassium–chrome–alum[b]	$\kappa = 1.6 \times 10^{-3}$	$\kappa = 32 \times 10^{-4}$ [c]	DeHaas and Gorter (1930)
	Fe–22Cr–13Ni–5Mn stainless steel	$\kappa = 2.1 \times 10^{-3}$	Antiferromagnetic	Ledbetter and Collings (1979)
Ferromagnetic	Low-carbon steel	$\mu_r = 5250$ (max.)	$\mu_r = 4900$ (max.)	McInturff and Claus (1970a)
	Si steel (1.8% Si)	$\mu_r = 6250$ (max.)	$\mu_r = 9700$ (max.)	McInturff and Claus (1970a)
Ferrimagnetic	Fe_3O_4	$\mu_r \geq 5.3$	$\mu_r \geq 5.5$	Jacobs (1959) – 4 K; Nagata (1961) – RT Assumes saturation at 0.11 $MA \cdot m^{-1}$ (1.4 kOe)
Antiferromagnetic	Fe–22Cr–13Ni–5Mn stainless steel	Paramagnetic	$\kappa = 6.0 \times 10^{-3}$	Ledbetter and Collings (1979)

[a] Si units
[b] $Cr_2(SO_4)_3 \cdot K_2SO_4 \cdot 24H_2O$
[c] $T = 14$ K

R.P. Reed, A.F. Clark (1983)



Materials for magnets: structural, cryogenics, vacuum: the LHC dipoles example

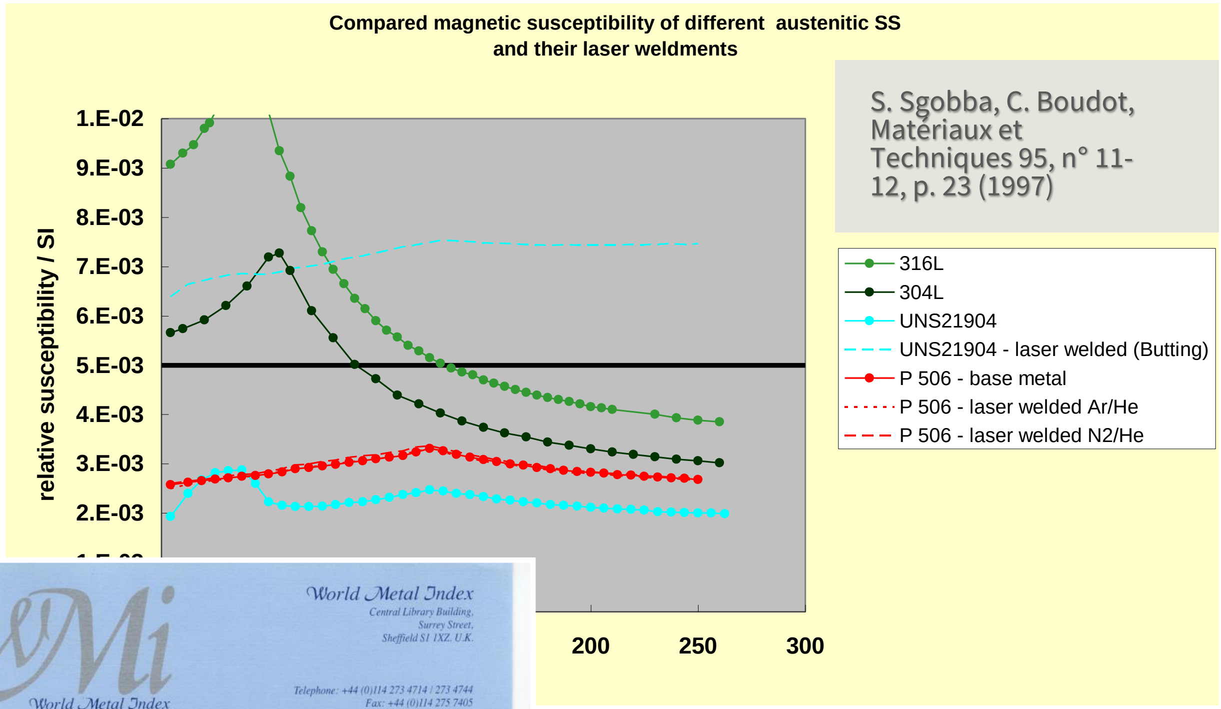
S. Sgobba, G. Hochoertler, A new non-magnetic stainless steel for very low temperature applications, Proc. Int. Congress Stainless Steel '99 : Science and Market, pp. 391-401

- **Magnetic permeability 1.005 max in the whole T range (4.2 K to RT)**
- **From electroslag remelted ingots**
- **Rolled strip, forged bars ⇒ extruded + drawn pipes**
- **Laser welding**

Development of a new stainless steel ("P506") for the LHC beam screen and the cooling capillaries

Challenging scope:

- Magnetic susceptibility ≤ $5{\cdot}10^{-3}$ at operating T in weld and parent material
- Fully stable
- Absence of hot cracking
- High strength and toughness (> 200 J)
- Thermal contraction not far from 316LN
- Corrosion behaviour ≈ 304L, 316LN
- Affordable price (several tens of km…)



S. Sgobba, C. Boudot, Matériaux et Techniques 95, n° 11-12, p. 23 (1997)

ADVANCED MATERIALS & PROCESSES/MARCH 2000

resistance to corrosion in reducing acid environments. Timetal 5111 Pd is fully corrosion resistant in concentrated geothermal brine at 230°C (445°F) and pH 2 to 3, both with and without the addition of 1000 ppm of ferric ions. Applications include marine environments where toughness and corrosion resistance are essential.

For more information: Timet Corp., Henderson Technical Laboratory, 8000 Lake Mead Drive, Henderson, NV 89015; tel: 702/566-4403; Web site: www.timet.com. Circle 129

[redacted]

A stainless steel that retains its non-magnetic properties even at very low temperatures has been developed in a joint project by Bohler Edelstahl GmbH, Austria, and CERN, Geneva, Switzerland. The alloy, designated P506, was developed specifically for a component of the Large Hadron Collider (LHC) under construction at CERN, the European Laboratory for Particle Physics. The alloy was designed for the "beam screen," a tube that is to be 15 meters (50 ft) long and 44 mm (1.7 in.) in diameter, with a wall thickness of one millimeter. The screen is to be continuously formed and laser welded.

"The stainless steel is readily weldable, not susceptible to hot cracking, and has high tensile properties, ductility, and toughness down to 4.2 kelvins (−452°F, −269°C)," says CERN materials engineer Stefano Sgobba.

The screen must be totally nonmagnetic, to prevent magnetic field distortion, and will be cooled to 10 to 20 kelvins (−442 to −423°F, −263 to −253°C).

For more information: [redacted]el: 41 2276-79401; e-mail: stefano.sgobba@cern.ch; Web site: www.cern.ch.

Aluminum/H₂O₂ fuel cells generate 20 times more power

A fuel cell that produces electricity through chemical reactions between hydrogen peroxide and aluminum is

NICKEL, VOL. 15, NO. 1, SEPTEMBER 1999

Exploring the Unknown

A new stainless steel is developed for Europe's Hadron collider

Böhler Edelstahl GmbH of Austria and CERN in Geneva, Switzerland, have jointly developed a new stainless steel that stays non-magnetic even at very low temperatures and maintains its magnetic properties after welding. Stainless steel P506 contains 11% nickel and 12% manganese and was developed specifically for the "beam screen," a component of the Large Hadron Collider (LHC) being constructed at CERN's European Laboratory for Particle Physics.

When it is switched on in 2005, the LHC will slam high-intensity proton beams together at energies previously impossible, thereby enabling scientists to observe, for the first time, phenomena that occured in the early universe, just after the "Big Bang."

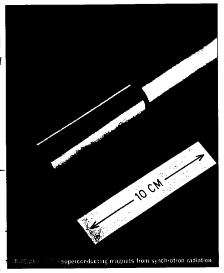
The beam screen will consist of a one-millimetre-thick, 15-metres-long perforated tube, measuring 44 millimetres in diameter. The tube will shield the vacuum chamber (in which superconducting magnets are housed) from the synchrotron radiation emitted by the circulating proton beam. The screen must be totally non-magnetic, thereby preventing magnetic field distortion. In addition, to keep a thermal equilibrium on the screen, the screen will be cooled to 10-20° Kelvin by gaseous helium. The screen will be continuously formed and laser-welded.

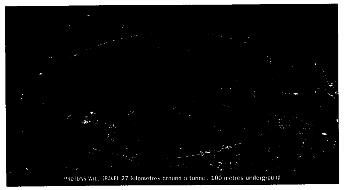
Tests have shown that the new stainless steel has a low value of magnetic permeability of less than 1.004, which is maintained over a temperature range of 4.2° Kelvin to room temperature.

"The stainless steel is readily weldable, is not susceptible to hot cracking, and has high tensile properties, ductility and toughness down to 4.2° Kelvin," says Stefano Sgobba, a materials engineer for the European Laboratory for Particle Physics.

These properties together with high resistance to corrosion, should prove useful in other low-temperature applications.

WEBSITE: www.lhc01.cern.ch/general/acphys.htm





IN SHORT

Quantum-Mechanically Speaking

Three solid-state physicists (two at Uppsala University in Sweden and one at the Sandia National Laboratories in Livermore, California) are offering a quantum-mechanical explanation for why Invar,™ a class of magnetic nickel alloys (K93600, for example) containing 36% nickel and 64% iron, exhibits almost no thermal expansion over a broad range of temperatures.

Due to this special behavior, Invar alloys are used primarily in shadow masks for television and computer screens to prevent screen distortion (see page 10, *Nickel*, Vol. 13, No. 3, March 1998) and in other applications such as high-precision instruments such as seismographs.

In the July 1, 1999, issue of *Nature*, Mark van Schilfgaarde, Igor Abrikosov and Borje Johansson provide a microscopic explanation for the Invar effect. For the first time, they allowed non-collinear spin ordering in their quantum mechanical calculations of the electronic and magnetic structure of these metals. At a low temperature, they demonstrated that the ground state is given by parallel ferromagnetic spin alignment. However, when the temperature increased (simulated by a decrease in volume), they showed that spins gradually depart from parallel alignment, so that the spin directions become increasingly disordered, with lower local moment amplitudes.

For Invar alloys, this decrease in volume compensates for the vibrational thermal expansion. The work is expected to keep solid-state physicists busy for years to come.

WEB SITE: www.nature.com

Australian Meat Processors

Dr. David Jenkinson, Director of NiDI Australia, will present a paper on the technical aspects of stainless steel in the meat processing industry at The Country Meatworks Association Annual Conference which is being held in Australia, October 11-12, 1999. The paper will cover alloy selection, fabrication/welding practice and the application of stainless in the handling of hot high- chloride waters. The meat industry is a large user of nickel stainless steel, particularly in abattoirs or slaughter houses.

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NICKEL, VOL. 15, NO. 1, SEPTEMBER 1999

WMi
World Metal Index

World Metal Index
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WMI/AEB
9.5.00

For more information: Stefano Sgobba, CERN, 1211 Geneva 23, Switzerland;

Dear Sirs

WORLD METAL INDEX

The World Metal Index (WMI) is an information service which provides users with the identification of metal grade, trade name or alpha-numeric reference number. It has developed over a period of more than thirty years in response to enquiries from companies; its coverage is world-wide. It contains references to both ferrous and non-ferrous materials.

The index itself contains information related to over 200,000 gra... information is backed by files of company trade catalogues and ... data compilations in addition to the extensive standards collectio... Business and Technology Library. The service is staffed by exp... personnel and is strictly confidential.

Appearance of your products in our index will advertise them to ... users.

In order to keep our collection of trade literature up to date, I wo... would supply me with:

technical information of the following grades of metal

see enclosure

as advertised in

Yours faithfully

A E Bagguley
Development Officer
World Metal Index

Stainless steel stays non-magnetic at low temperatures

A stainless steel that retains its non-magnetic properties even at very low temperatures has been developed in a joint project by Bohler Edelstahl GmbH, Austria, and CERN, Geneva, Switzerland. The alloy, designated P506, was developed specifically for a component of the Large Hadron Collider (LHC) under construction at CERN, the European Laboratory for Particle Physics. The alloy was designed for the "beam screen," a tube that is to be 15 meters (50 ft) long and 44 mm (1.7 in.) in diameter, with a wall thickness of one millimeter. The screen is to be continuously formed and laser welded.

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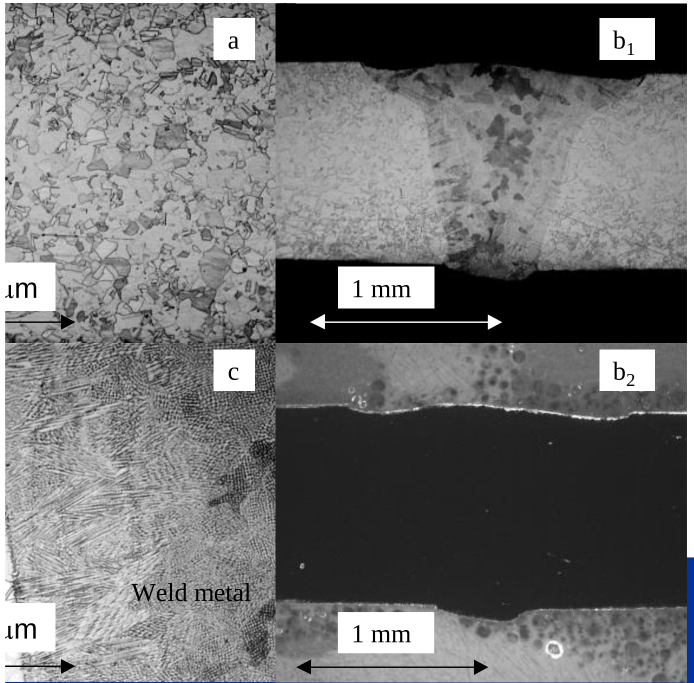
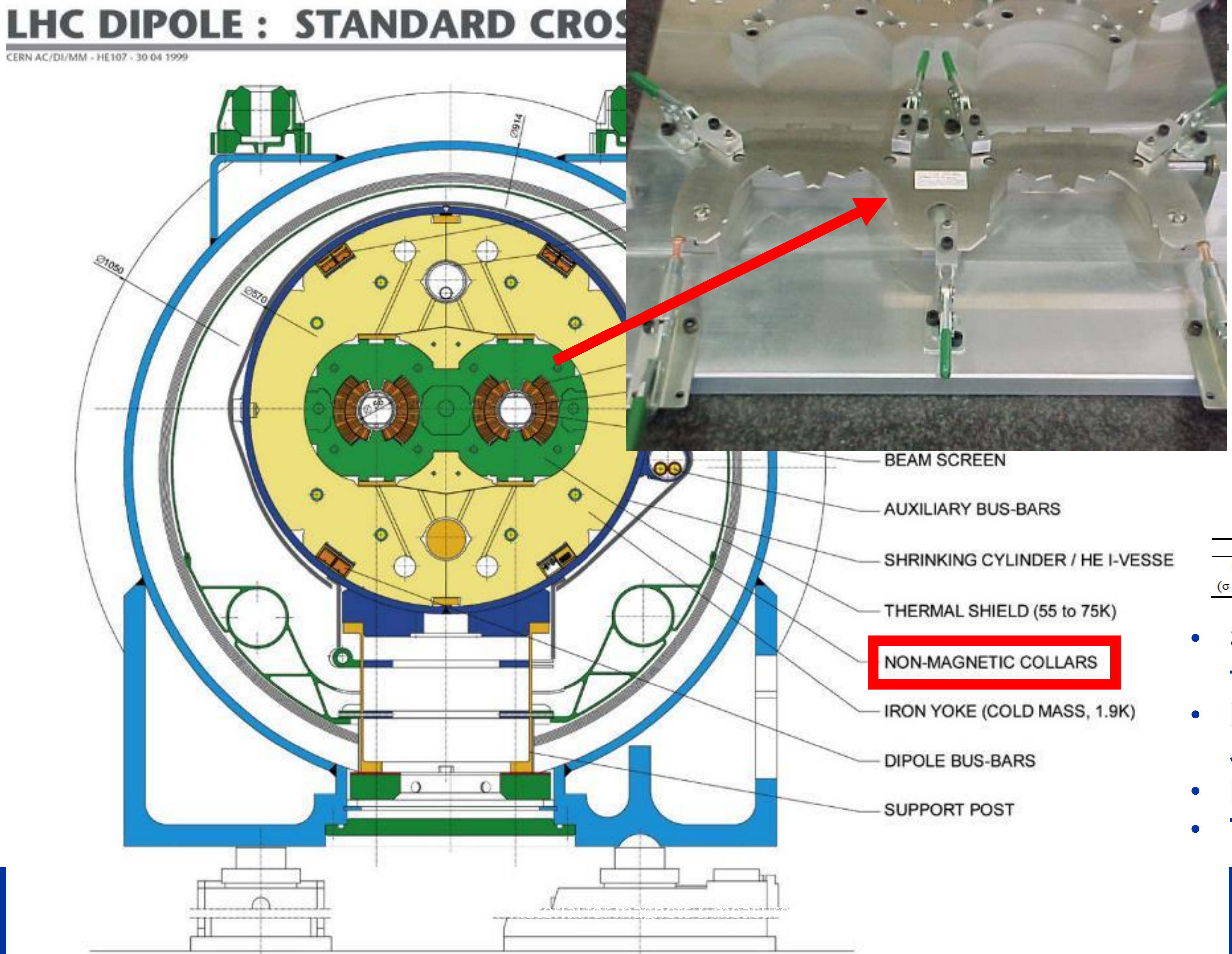
p12

H/WMIGrade





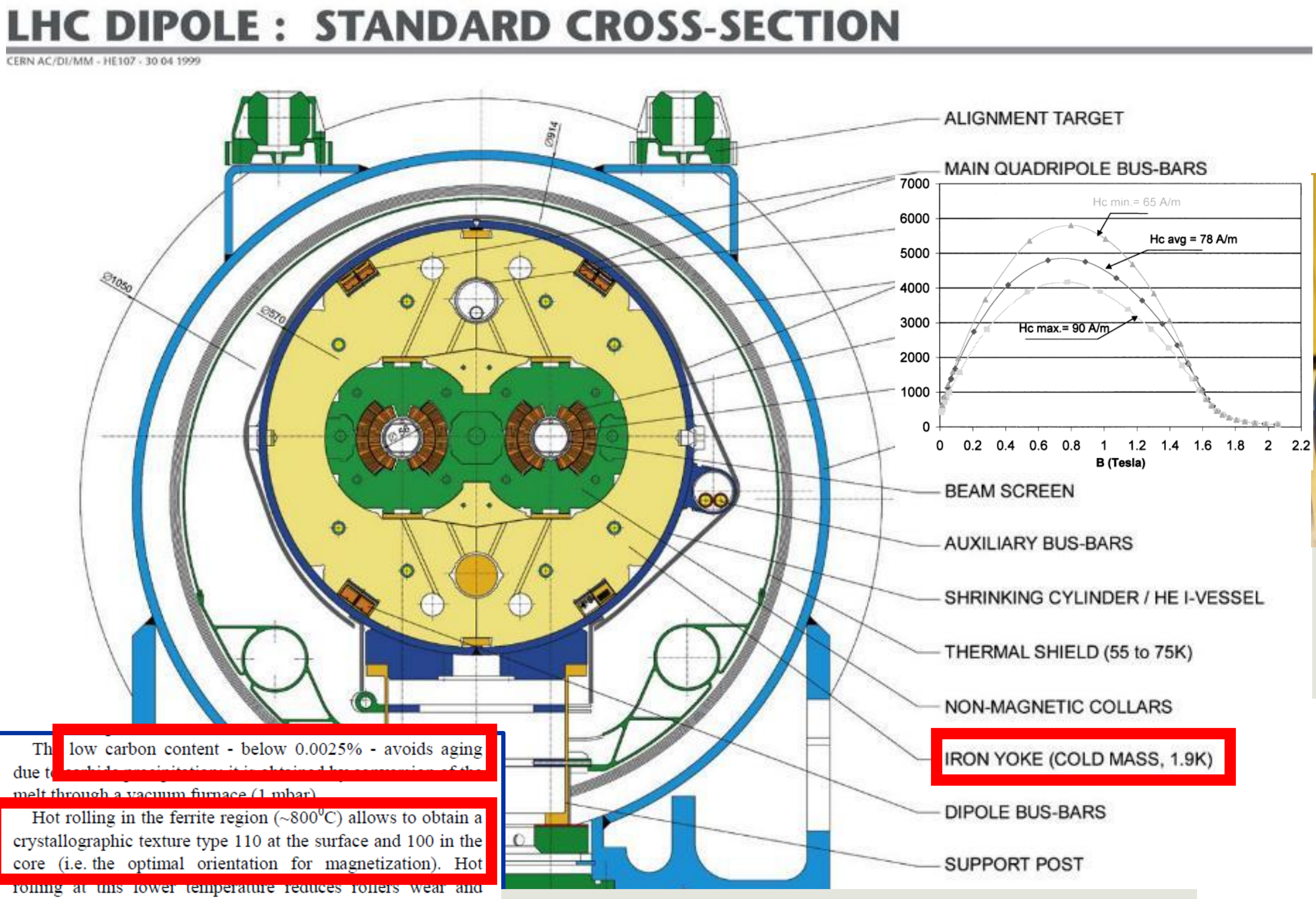
Materials for magnets

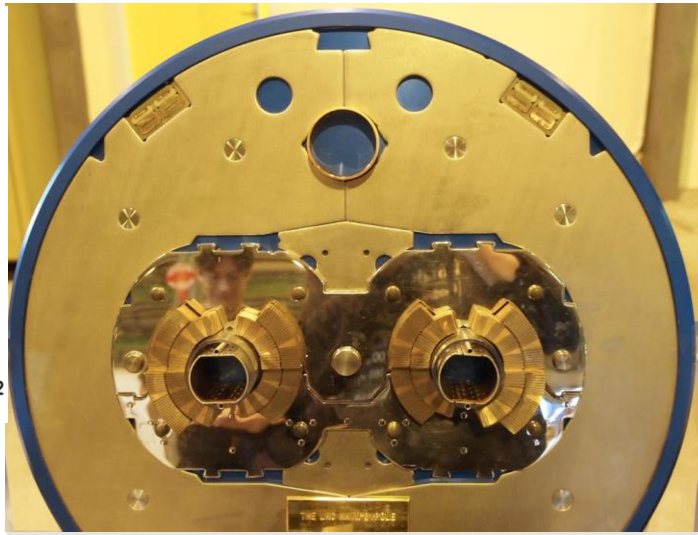
Table I. Chemical composition of melts (% weight)

C	Mn	Ni	Cr	Mo	Si	N
0.086	11.5	6.61	17.77	0.09	0.42	0.30
(σ =0.005)	(σ =0.2)	(σ =0.06)	(σ =0.07)	(σ =0.02)	(σ =0.04)	(σ =0.01)

- **Stainless steel "Nitronic 40" type (YUS 130S ~ UNS 21904)**
- **In kind contribution from Japan (Nippon Steel)**
- **Rolled strip, 11000 t**
- **Twelve million collars**

Materials for magnets





S. Babic et al., Toward the Production of 50 000 Tonnes of Low-Carbon Steel Sheet for the LHC Superconducting Dipole and Quadrupole Magnets, https://doi.org/10.1109/TASC.2002.1018621

The low carbon content - below 0.0025% - avoids aging due to carbide precipitation; it is obtained by conversion of the melt through a vacuum furnace (1 mbar).

Hot rolling in the ferrite region (~800°C) allows to obtain a crystallographic texture type 110 at the surface and 100 in the core (i.e. the optimal orientation for magnetization). Hot rolling at this lower temperature reduces rollers wear and fabrication costs, improves steel surface quality and flatness, and allows the formation of a stable, protective layer of mill scale.

During the annealing heat treatment, the energy stored in the steel with hot rolling allows grain size growth.

F. Bertinelli et al., "Production of Low-Carbon Magnetic Steel for the LHC Superconducting Dipole and Quadrupole Magnets," in IEEE Transactions on Applied Superconductivity, vol. 16, no. 2, pp. 1777-1781, June 2006, doi: 10.1109/TASC.2006.873236

- **Ultra Low Carbon steel "Magnetil" type**
- **Rolled strip, 50000 t**

Materials for magnets: structural, cryogenics, vacuum: the LHC dipoles example

- 3000 tonnes of 1.4429 (316LN) stainless steel plates delivered by ArcelorMittal Industeel /FR
- 41 km of half-shells, Ø 550 mm, 15 m length, 10.1 mm thick produced by Butting /DE

- **Ingot casting ⇒ Forged slabs ⇒ rolled plates**
- **MIG/MAG welding (STT) – special cryogenic filler**

METAL POWDER INDUSTRIES FEDERATION

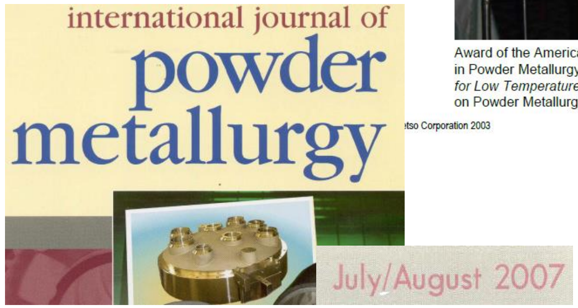
PM Design Competition Award Winner

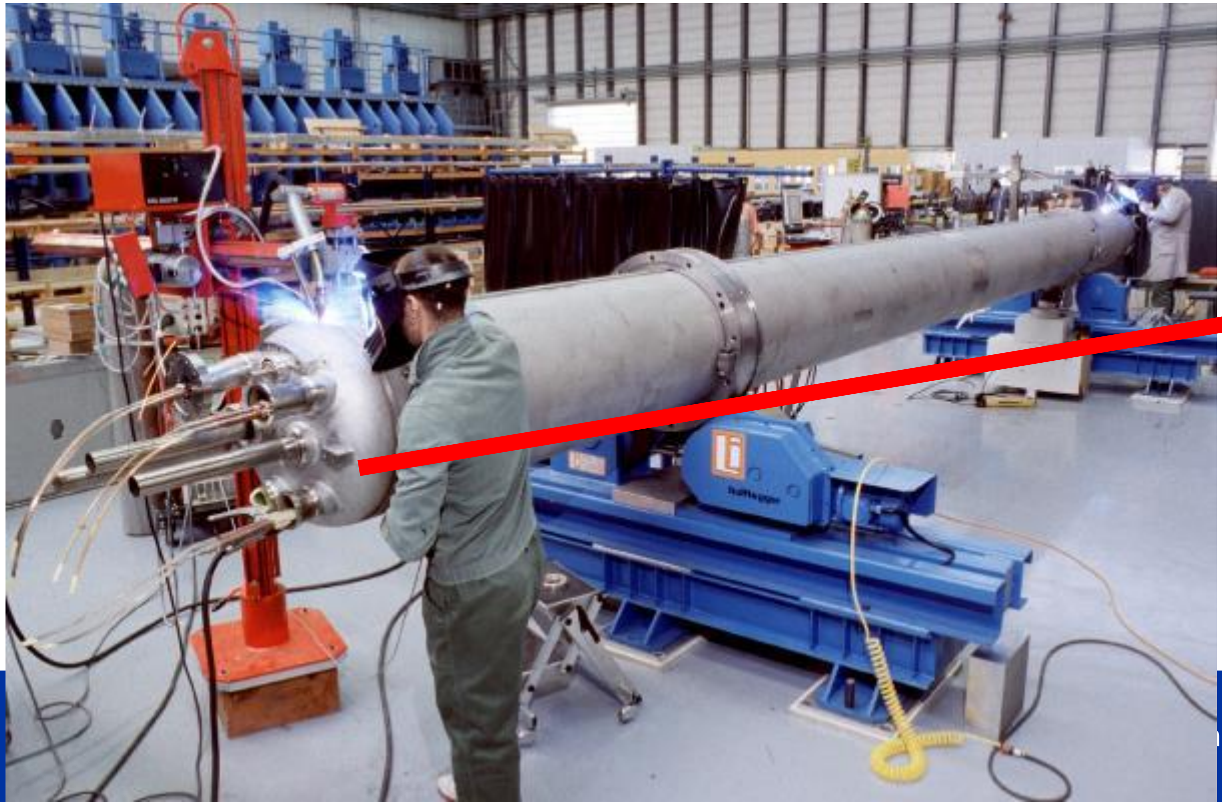
Grand Prize, reception at the PM Part Competition at PowderMet 2007, The International Conference on Powder Metallurgy and Particulate Materials, Denver-CO, May 13-16, 2007

Award: Grand Prize
Year: 2007

Award of the American Society for Metals (ASM International, Finland) for Outstanding Achievements in Powder Metallurgy, to the paper "*Powder HIP End Covers for CERN LHC Project, High Technology for Low Temperatures*", 6th Annual Powder Metallurgy Network Seminar, Engineering Solutions Based on Powder Metallurgy, Tampere 29th - 30th January, 2004

metso





SHRINKING CYLINDER HE I-VESSEL

THERMAL SH... **end covers**

NON-MAGNETIC COLLARS

IRON YOKE (COLD MASS, 1.9K)

DIPOLE BUS-BARS

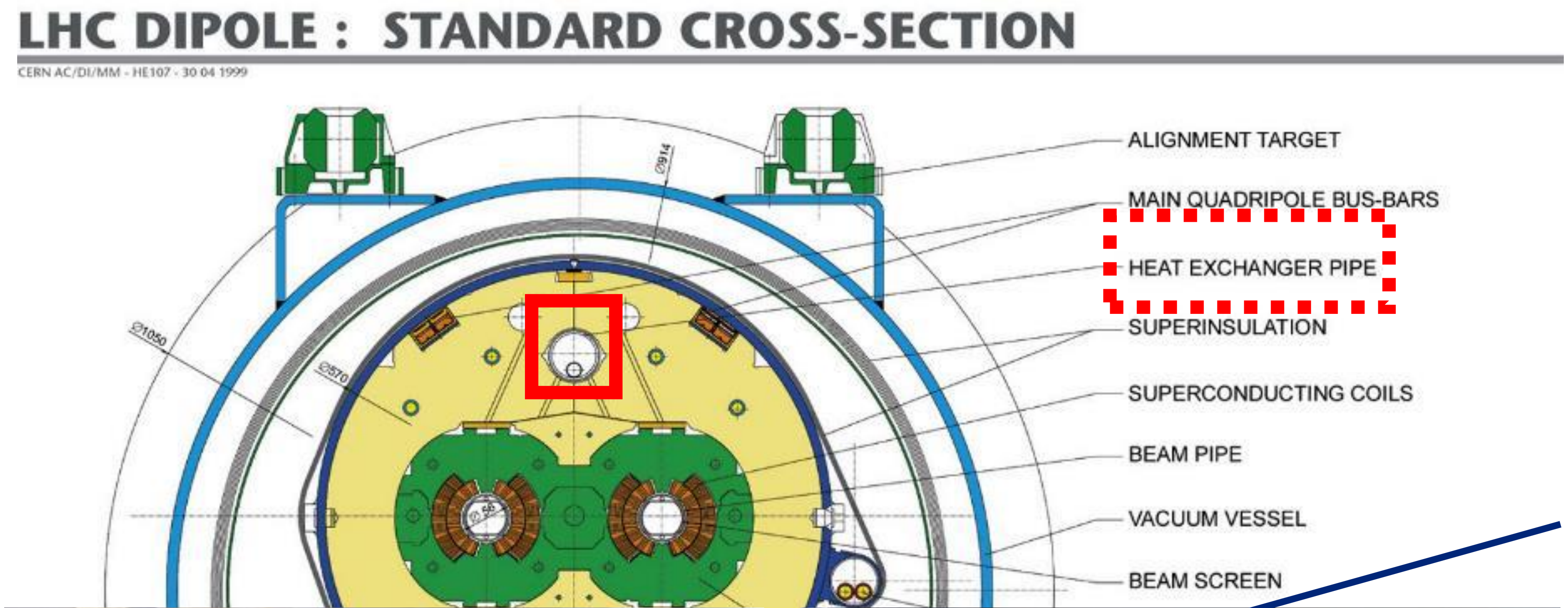
SUPPORT POST

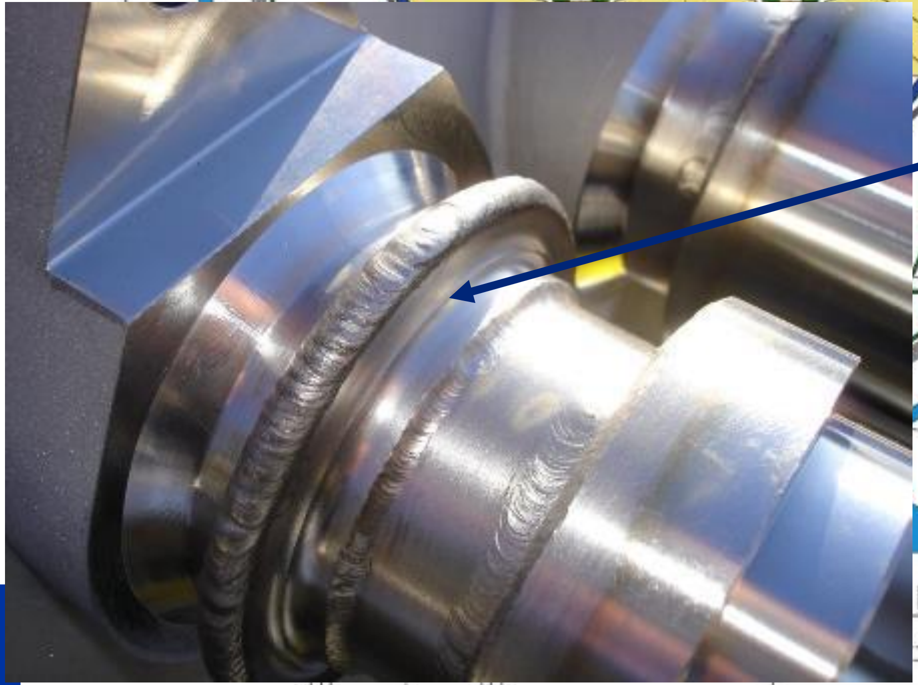
- Leak tight to gazeous He at 300 K
- Leak tight to superfluid He at 1.9 K
- 25 thermal cycles down to 1.9 K

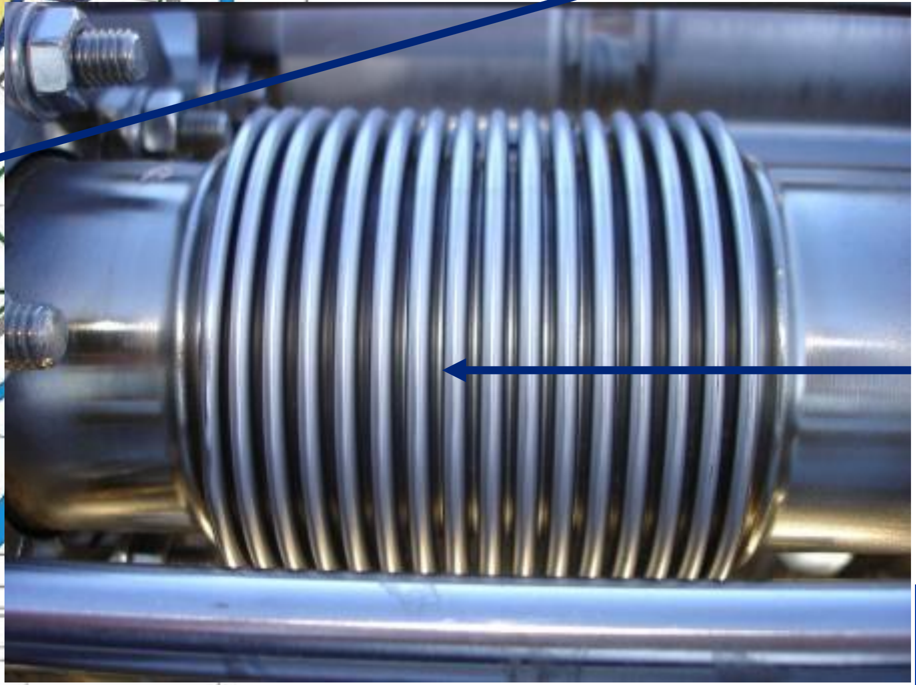
- **High ductility and toughness at low T**
- **Compatible with its environment (316LN)**
- **Cost effective**

- **Powder metallurgy + HIPing**
- **MIG/MAG & TIG welding**

S. Sgobba et ... *Stainless Stee... Temperature...* Metallurgy W... Kyoto, Japan, vol. 2, p. 1002-1005





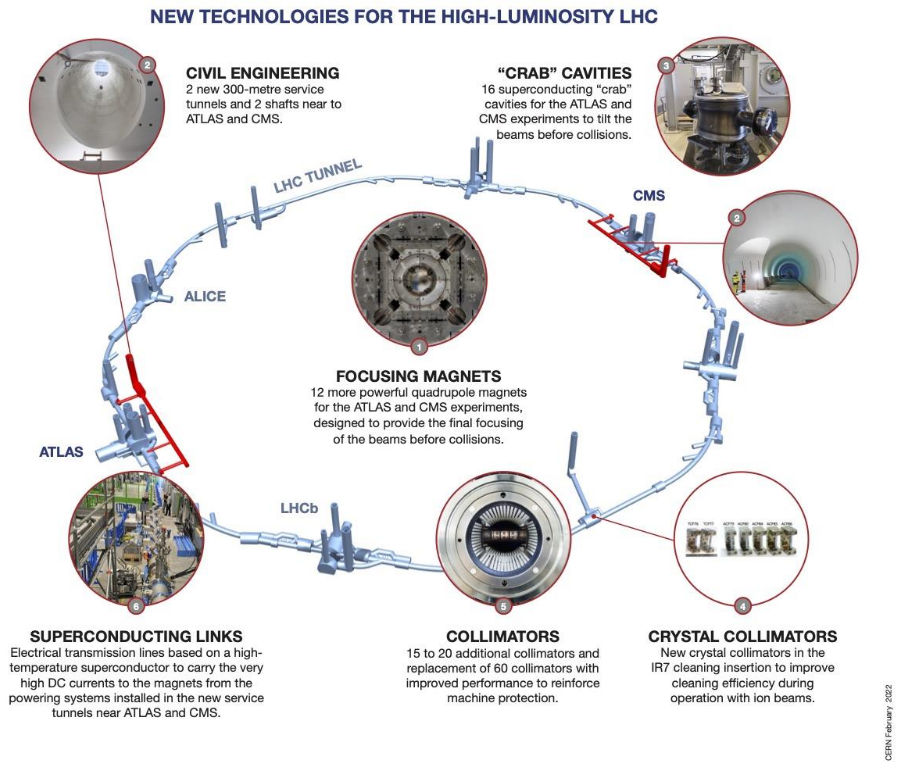


Materials for magnets…

- Multidirectionally forged 316LN (1.4429) flanges/sleeves
- From electroslag remelted ingots

- Special 316L (1.4435, high Ni+Cr), from electroslag remelted ingots
- Strip
- Hydroformed bellows

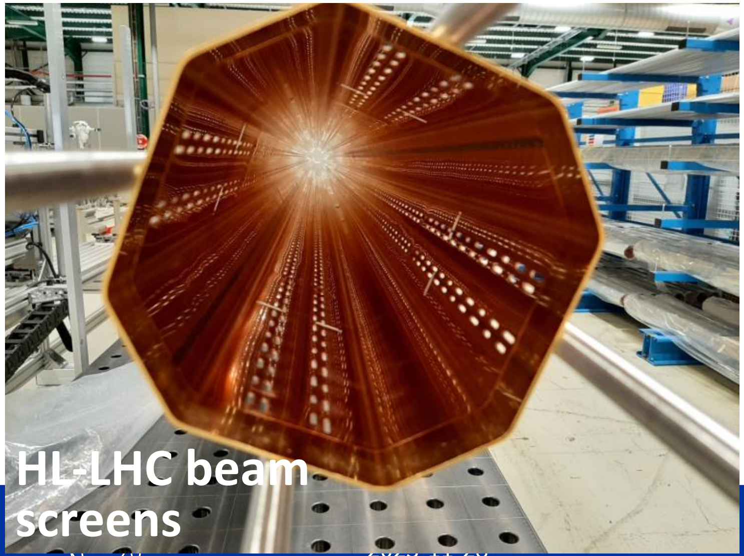
Materials for magnets: HL-LHC



Fine-blanked collars

F712 contract

- More than 450 tonnes of austenitic stainless steel strips
- Same stainless steel specification as for the LHC



Beam screen

HL-LHC implies:

- 3.1 km of finished strip;
- 4600 m of seamless cold-drawn cooling tubes in lengths of up to 14 m
- Same stainless steel as for the LHC

IT-4203/TE/**HL-LHC**

3.1.1 Special austenitic grade stainless steel strip (CERN supply)

The chemical composition of the CERN supplied stainless steel strip is given in table 2.

Table 2 - Typical chemical composition (weight-%) of the CERN supplied stainless steel strip.

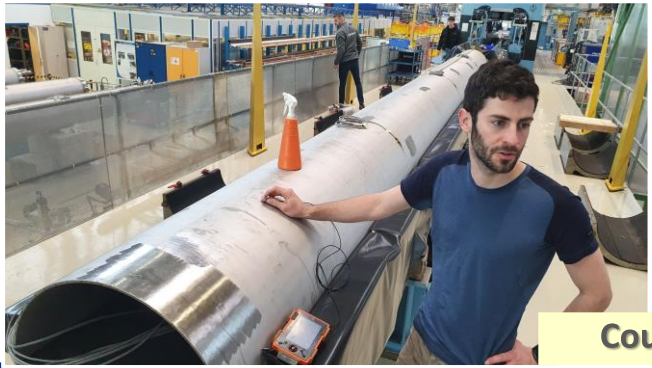
%	C	Cr	Mo	Ni	Mn	Si	N	Cu	S	P	B	Co
Min		19.0	0.8	10.7	11.8		0.30					
Max	0.03	19.5	1.0	11.3	12.4	0.5	0.33	0.15	0.002	0.02	0.002	0.1

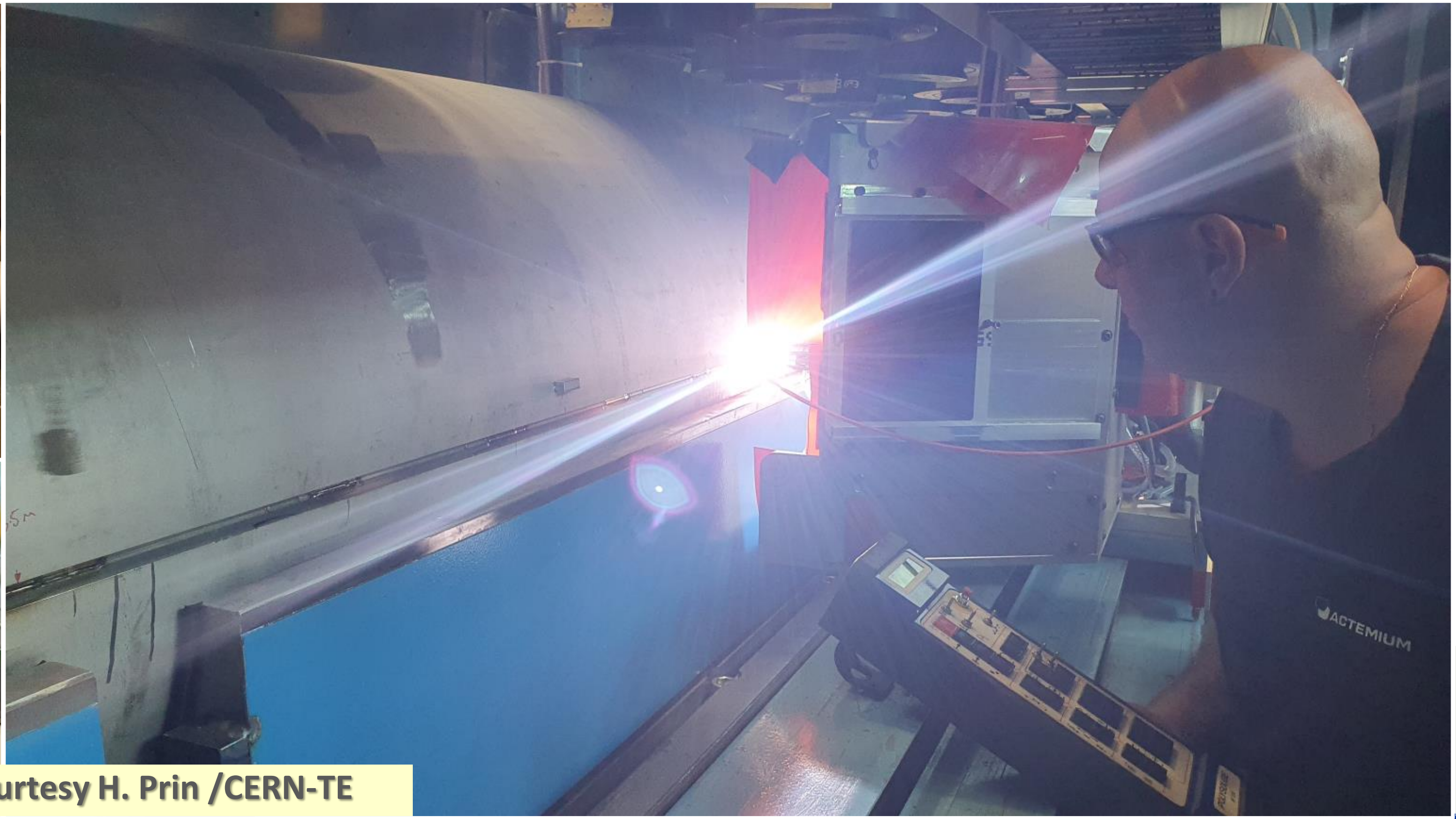
Materials for magnets: HL-LHC

HL-LHC further 316LN plate production and forming (2015-16)

- Supplied by Arcelor Mittal Industeel
- 15 mm x 6.5 m (11T project)
- 8 mm x 6.5 m and 10 m for WP3 (Q2, CP et D2)

Courtesy AP TELA OY /FI





Courtesy H. Prin /CERN-TE

Shrinking and inertia cylinders

Materials for magnets: stainless steels

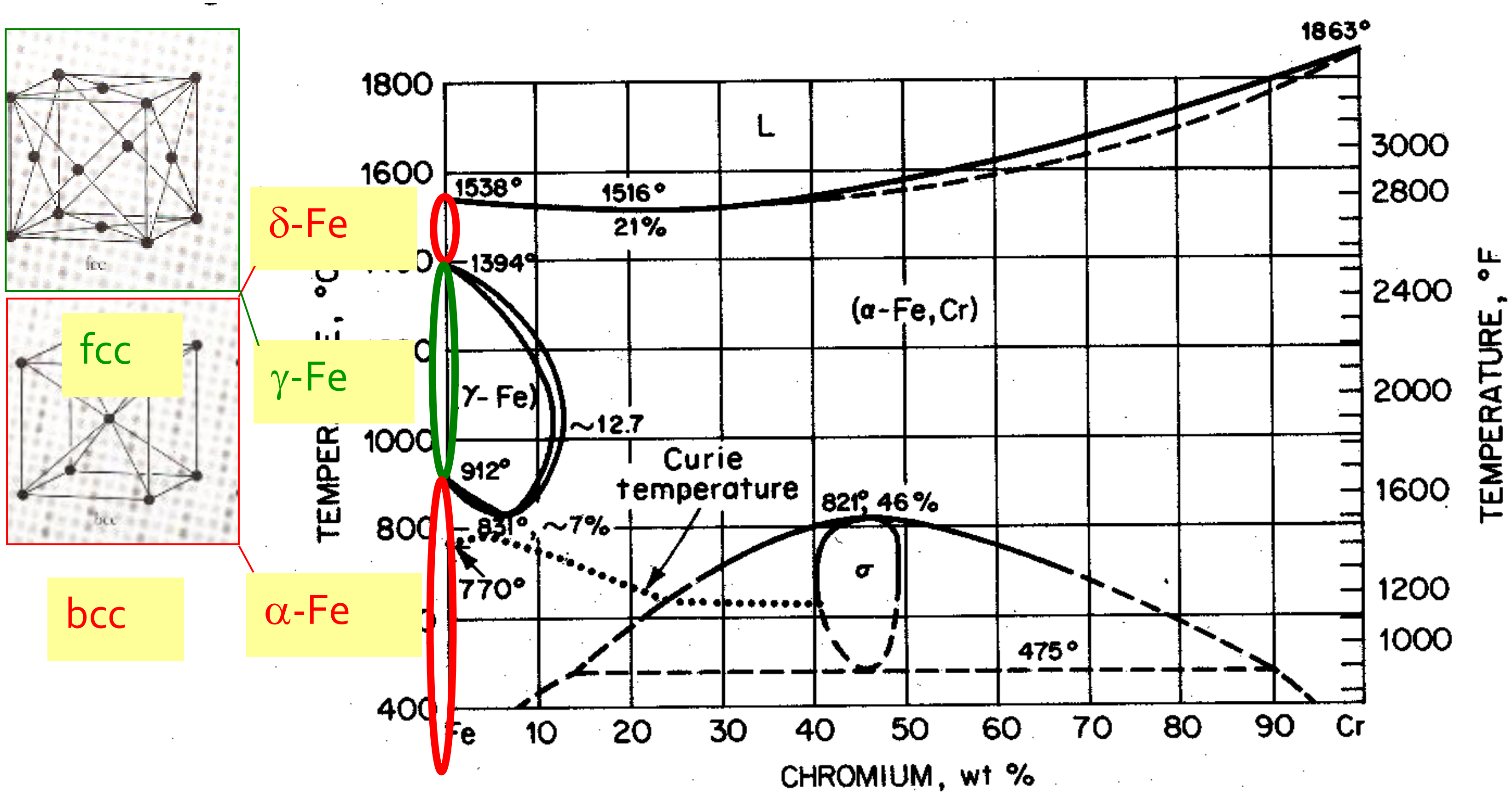


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

Stainless steel: iron alloys containing a minimum of approx. 11 % Cr

Materials for magnets: austenitic stainless steels

AISI 304, the "18-8" or "18-10" stainless (18%Cr, 8-10%Ni)

fork_&_knives

- forr fcc (FeC
- γ-lo
- γ-ph enla
- forr sup forr
- trar can sup allo

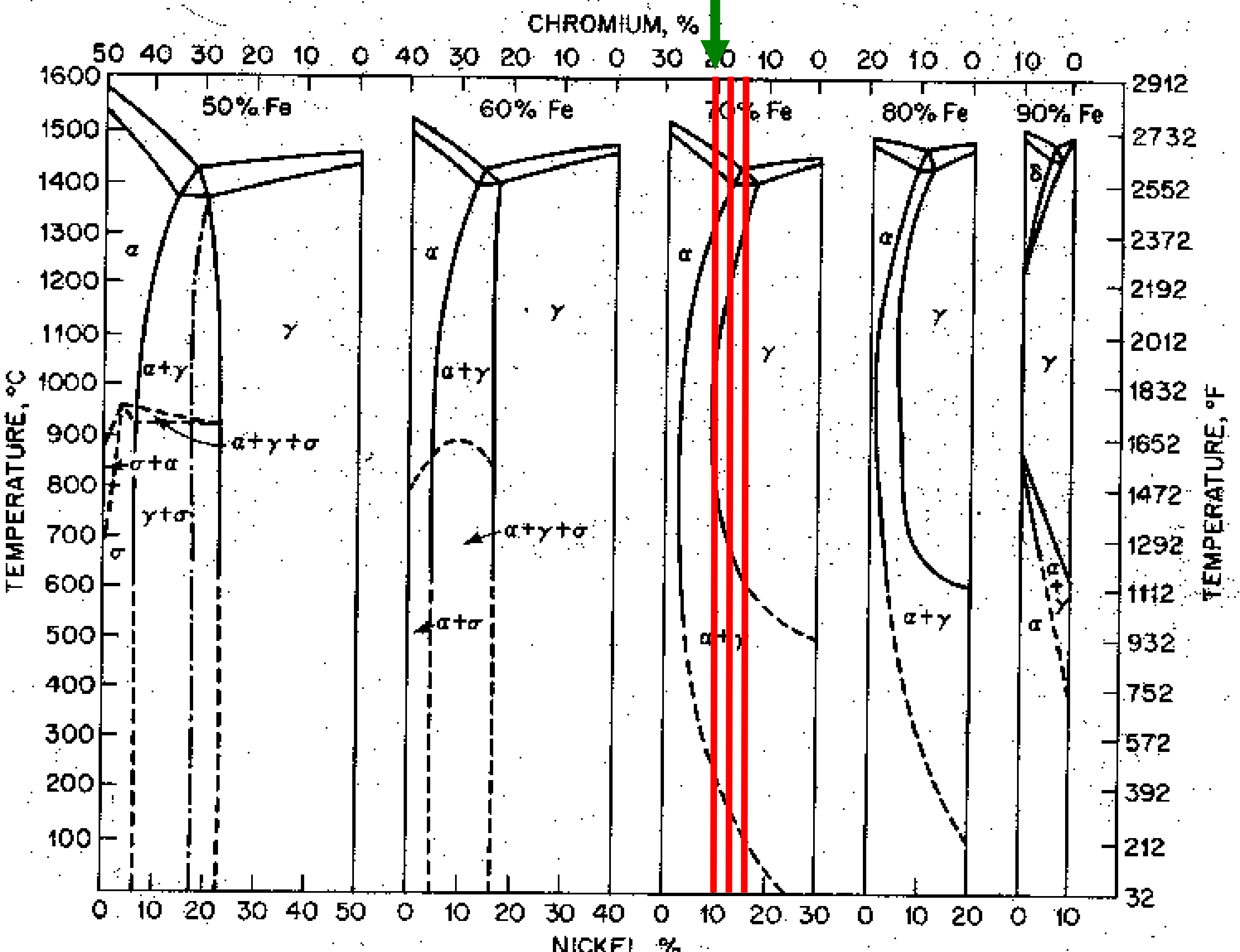


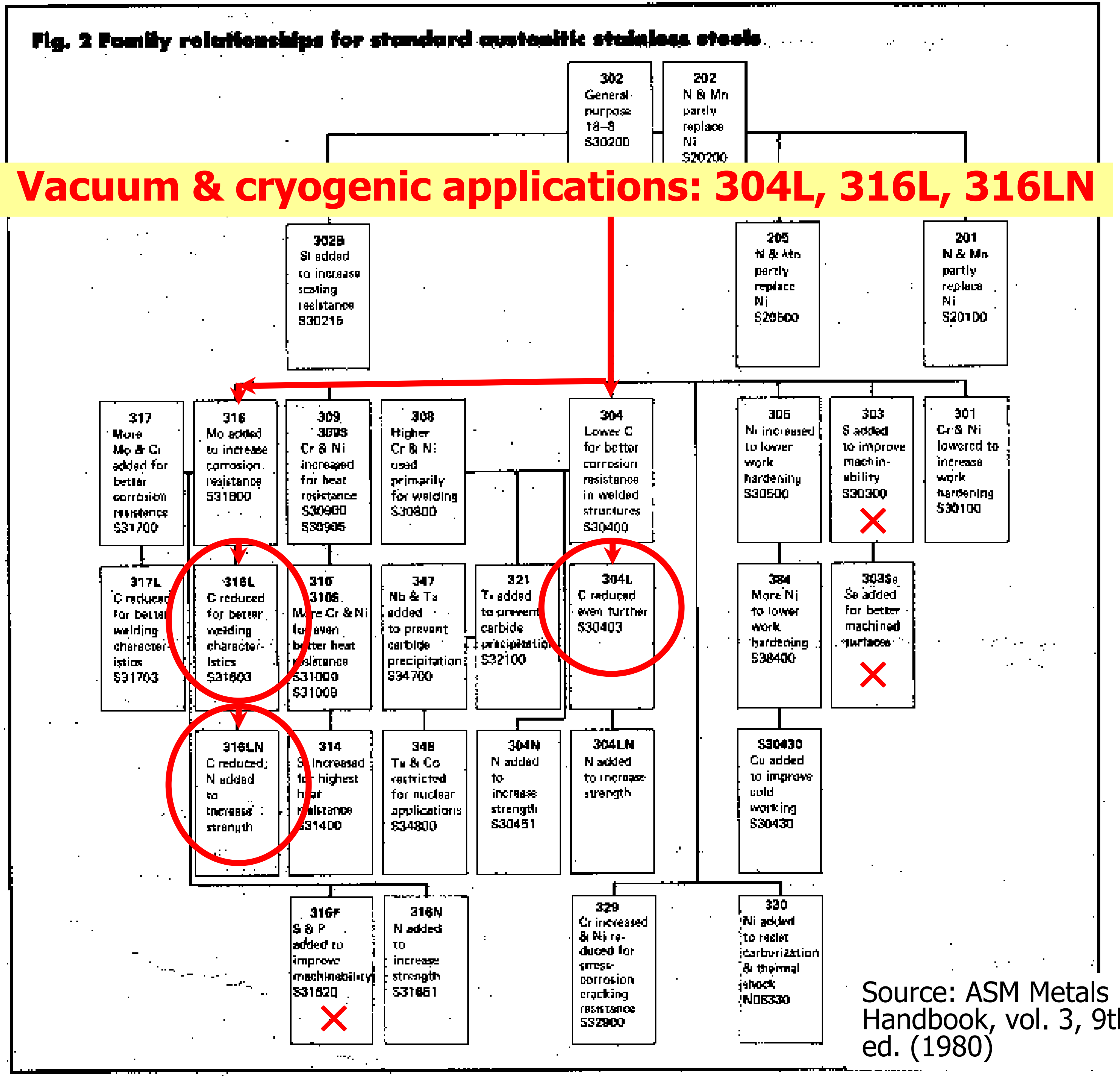
Fig. 14 Cross sections of Fe-Cr-Ni ternary.[26]

291, 8th ed.,

Materials for magnets: austenitic stainless steels

More: https://cds.cern.ch/record/2723993?ln=en
&:

Mechanical Materials Engineering
2 - 15 June 2024
Sint-Michielsgestel, Netherlands
Registration will open soon



Vacuum & cryogenic applications: 304L, 316L, 316LN

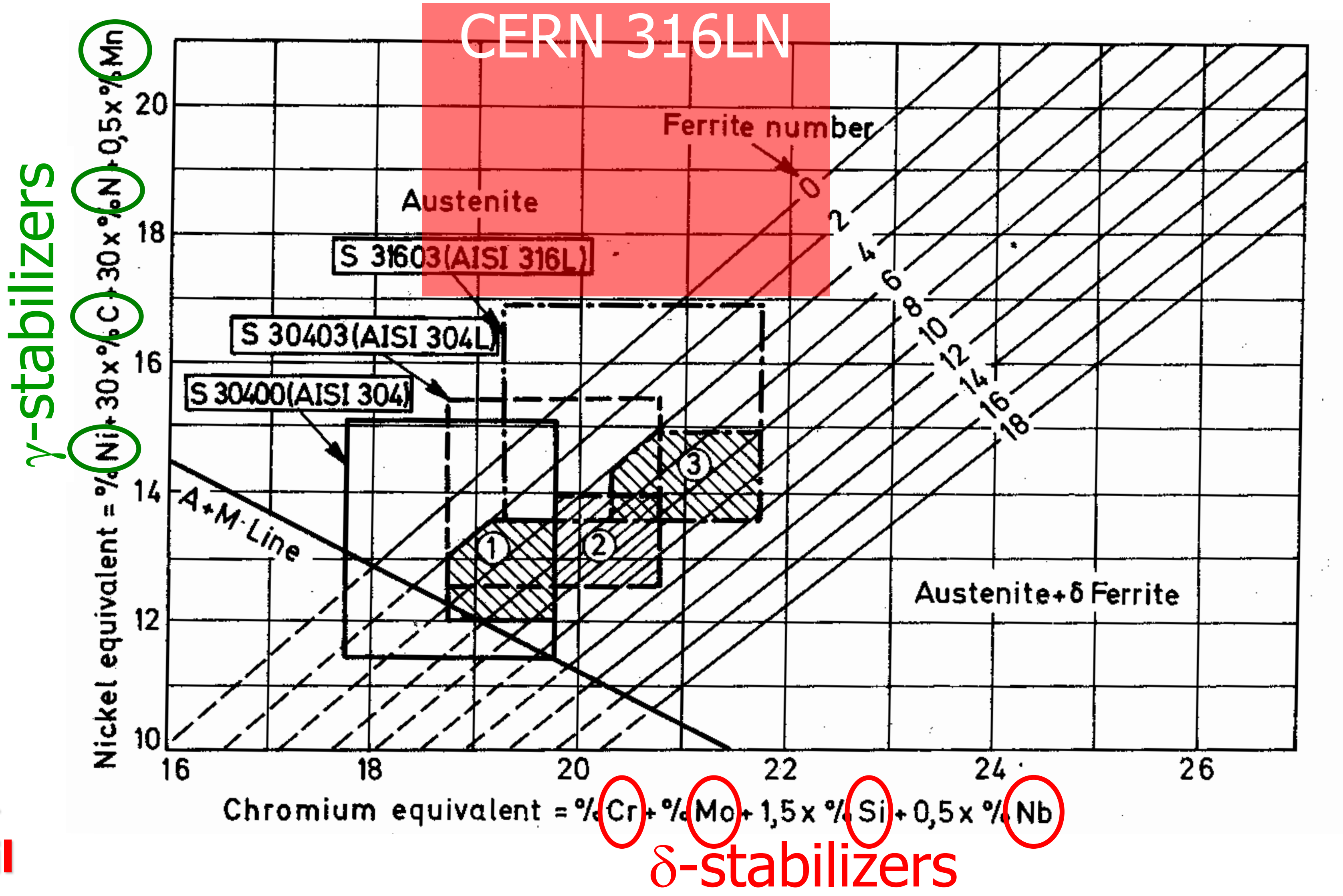
Source: ASM Metals Handbook, vol. 3, 9th ed. (1980)

Materials for magnets: austenitic stainless steels

CERN 316LN

Element	Chemical composition (product analysis) % by mass
Cr	16.00 – 18.50*
Ni	12.00 – 14.00*
C	0.030 max.
Si	1.00 max.
Mn	2.00 max.
Mo	2.00 – 3.00*
N	0.14 – 0.20*
P	0.030 max.*
S	0.010 max.*
Fe	Remainder

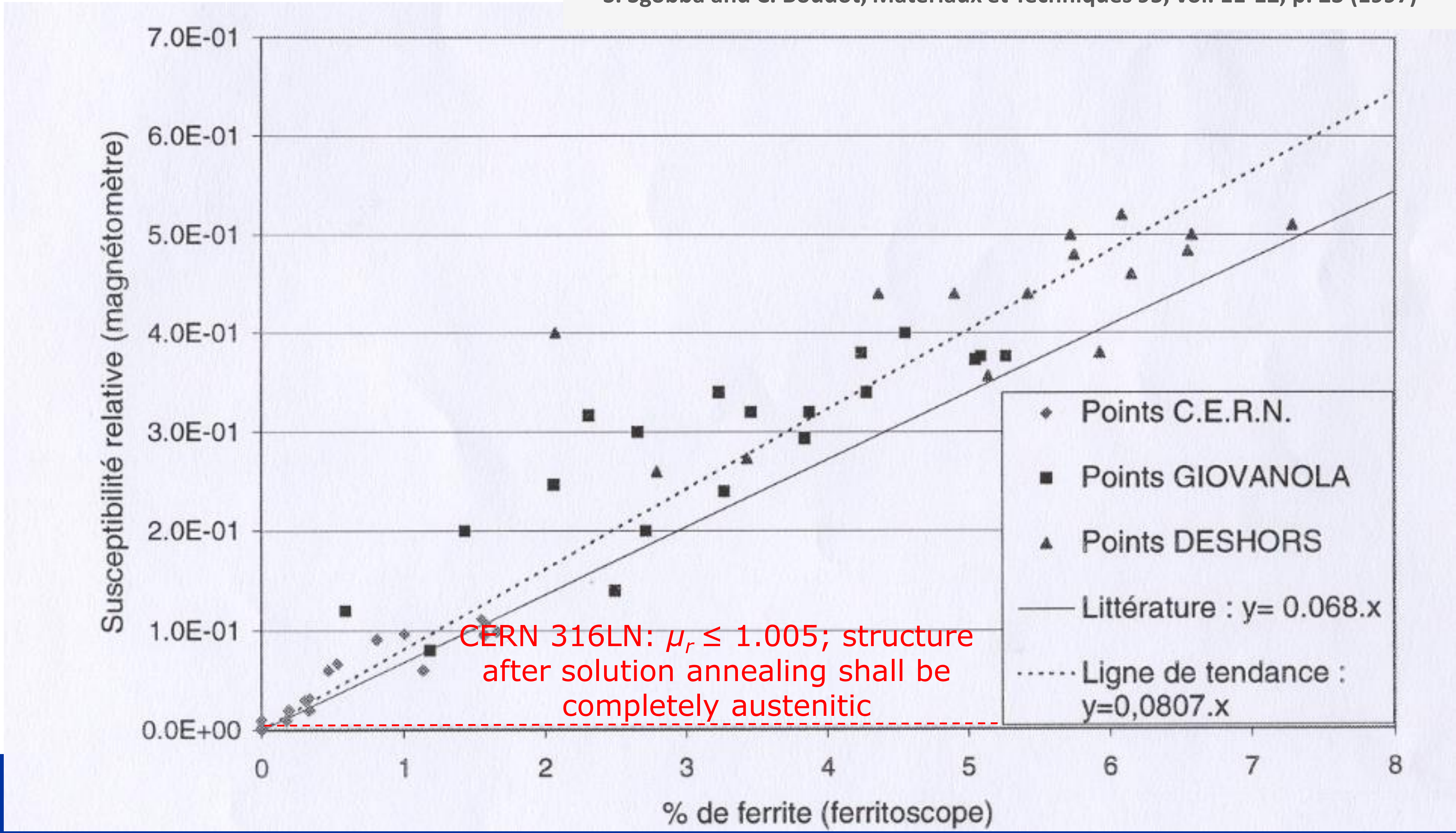
* CERN requirement



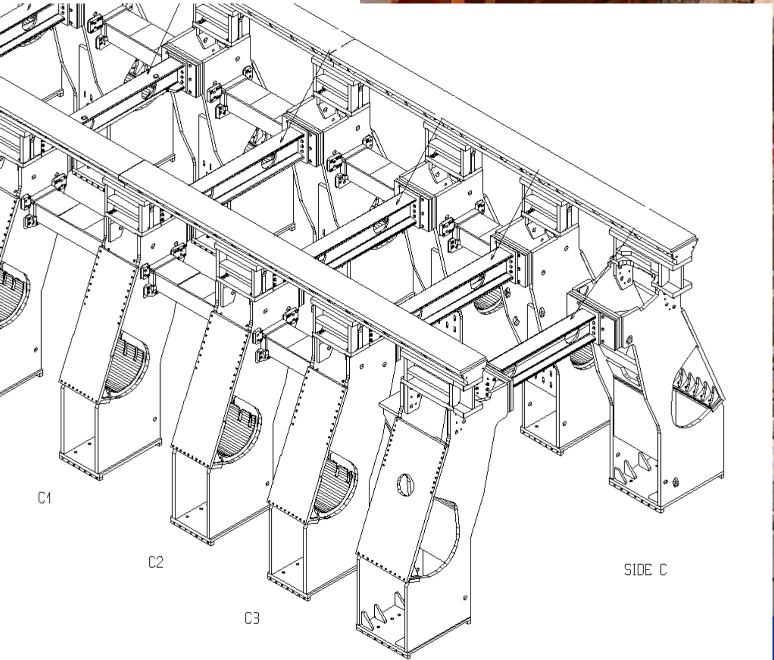
Maximum allowed magnetic permeability μ_r = 1.005 at RT → allowed content of δ-ferrite is nil

Materials for magnets: austenitic stainless steels

S. Sgobba and C. Boudot, Matériaux et Techniques 95, vol. 11-12, p. 23 (1997)



Materials for magnets: austenitic stainless steels – ATLAS feet



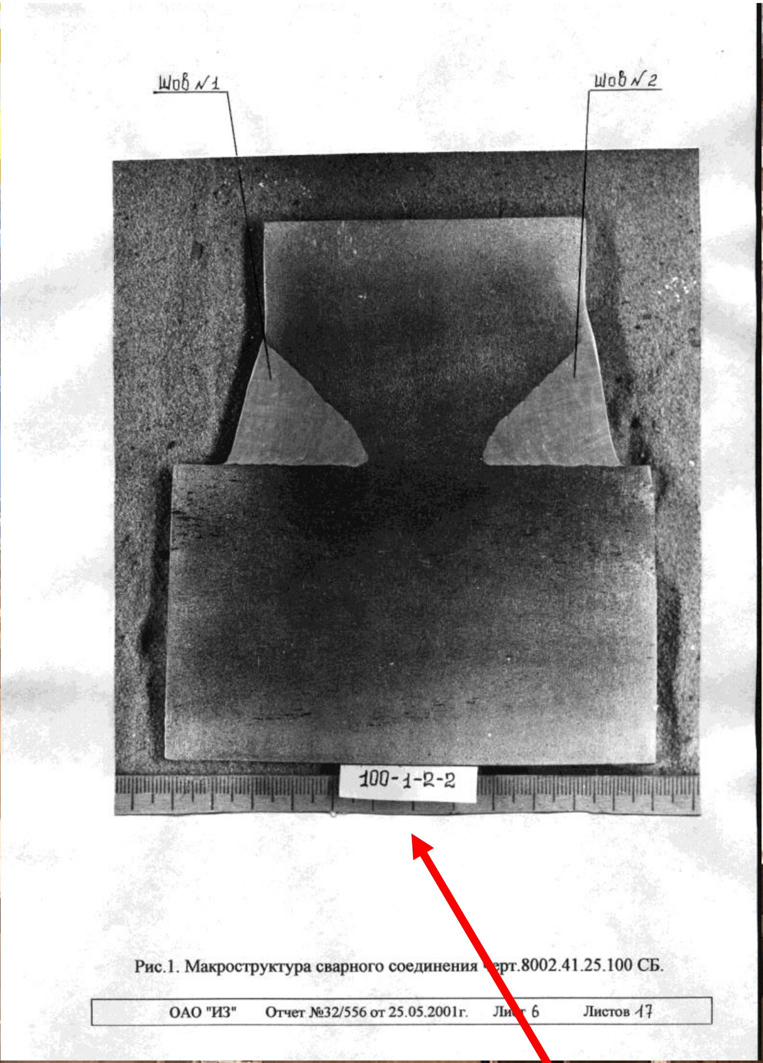
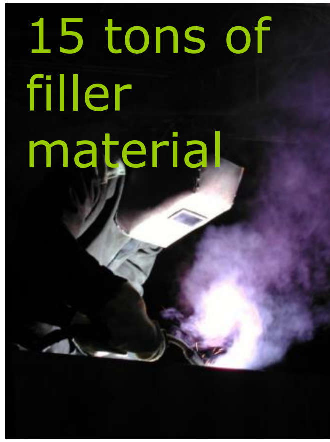


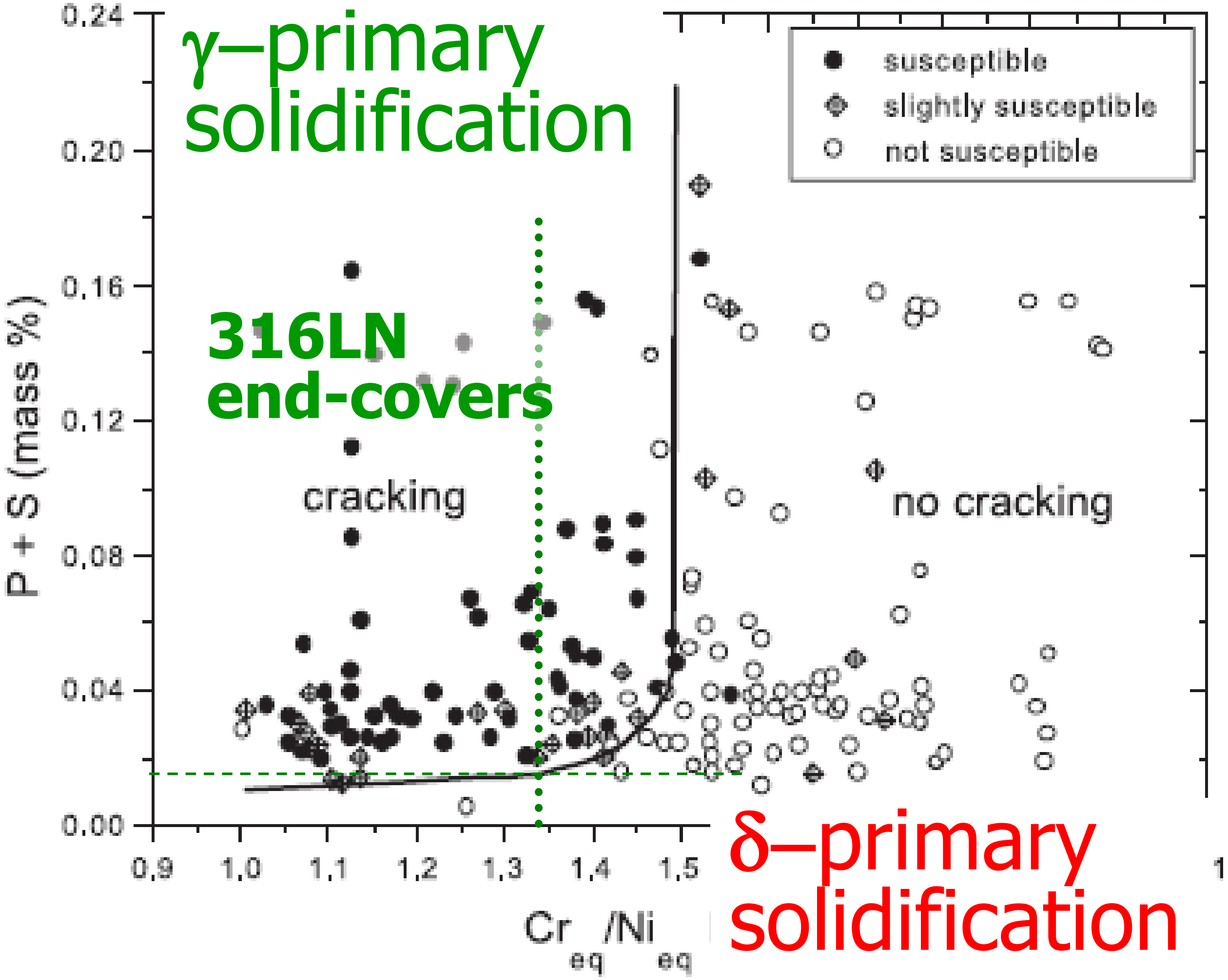
Рис.1. Макроструктура сварного соединения черт.8002.41.25.100 СБ.

ОАО "ИЗ" Отчет №32/556 от 25.05.2001г. Лист 6 Листов 17

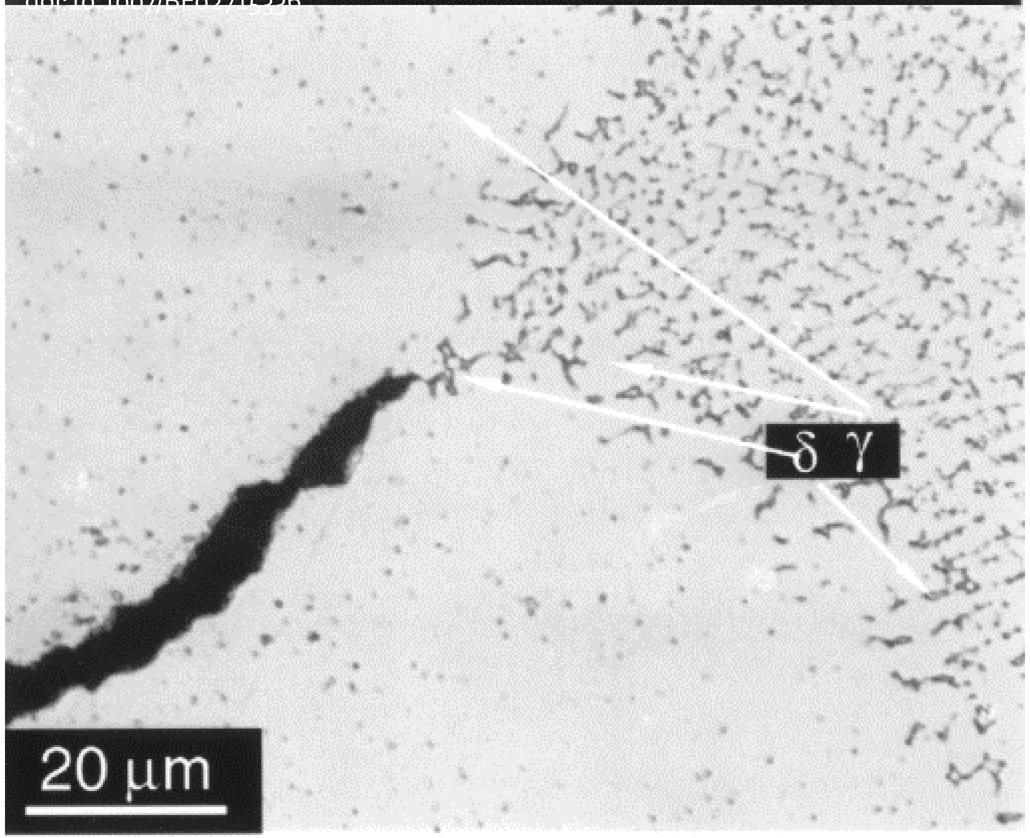


15 tons of filler material

Materials for magnets: austenitic stainless steels



Korinko, P.S. & Malene, S.H. Practical Failure Analysis (2001) 1: 61. doi:10.1007/BF02715336

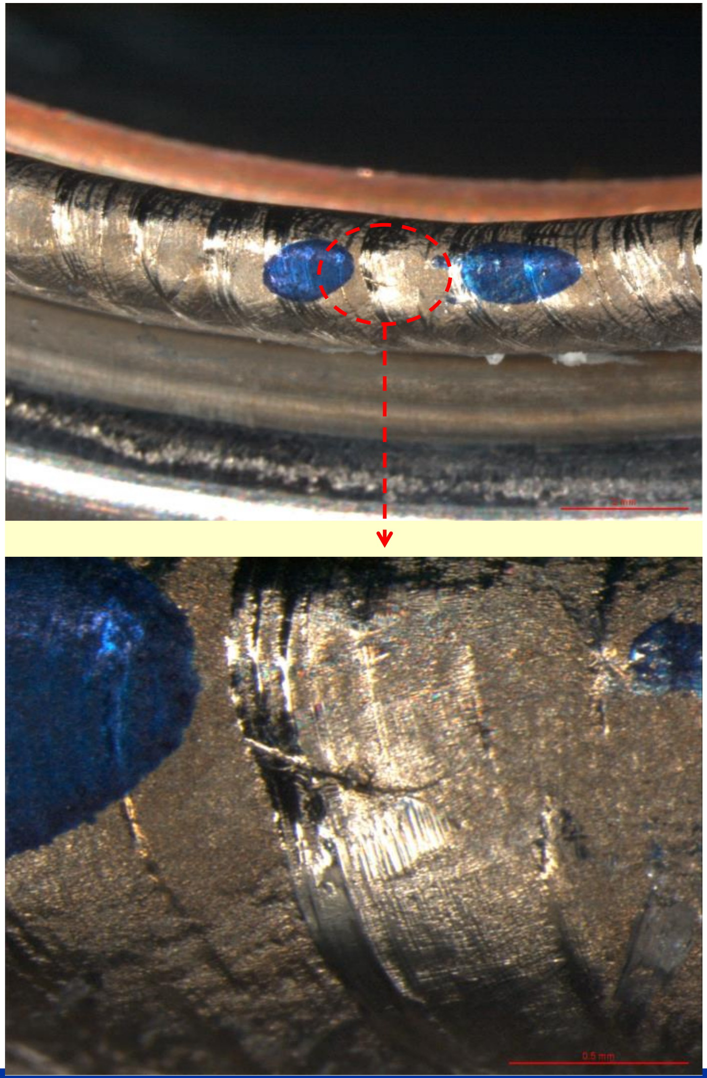


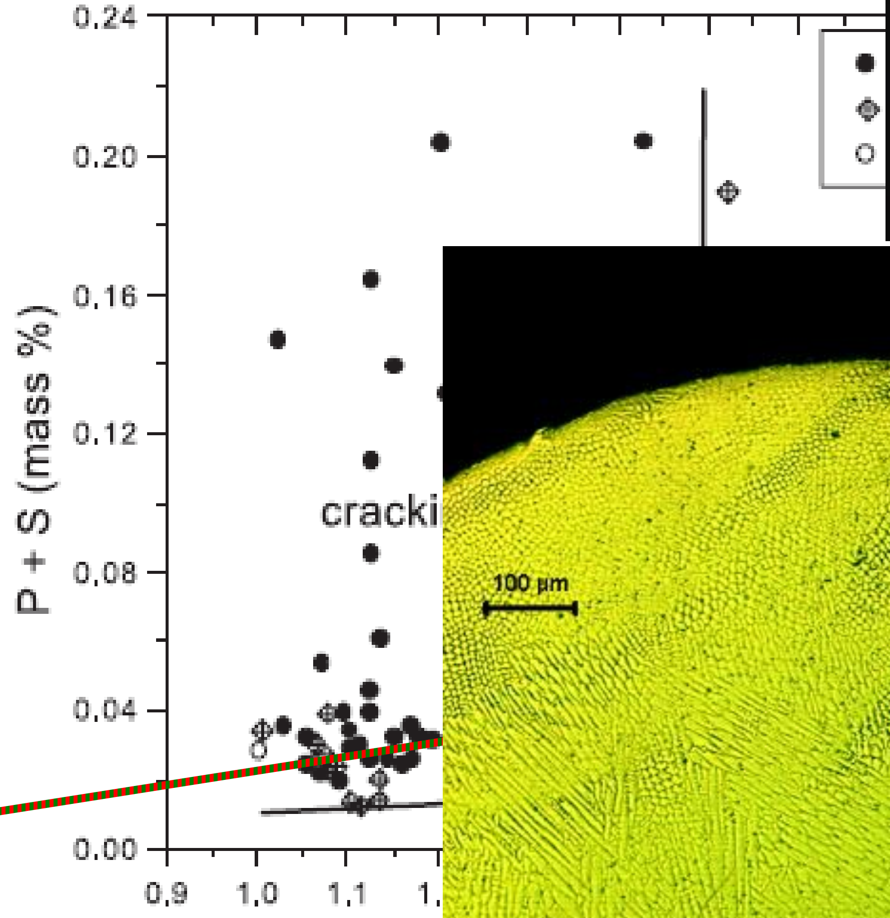
Schaeffler equivalent formulae for Cr_{eq} and Ni_{eq}

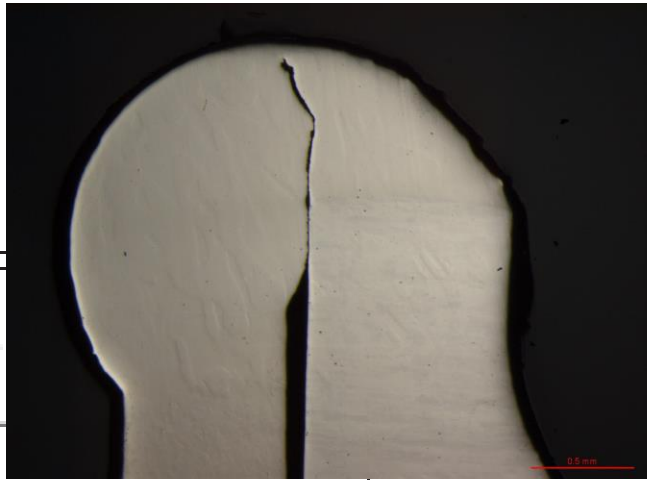
$$Cr_{eq} = Cr + 1.5Si + 1.37Mo$$

$$Ni_{eq} = Ni + 0.31Mn + 22C + 14.2N$$

Materials for magnets: austenitic stainless steels

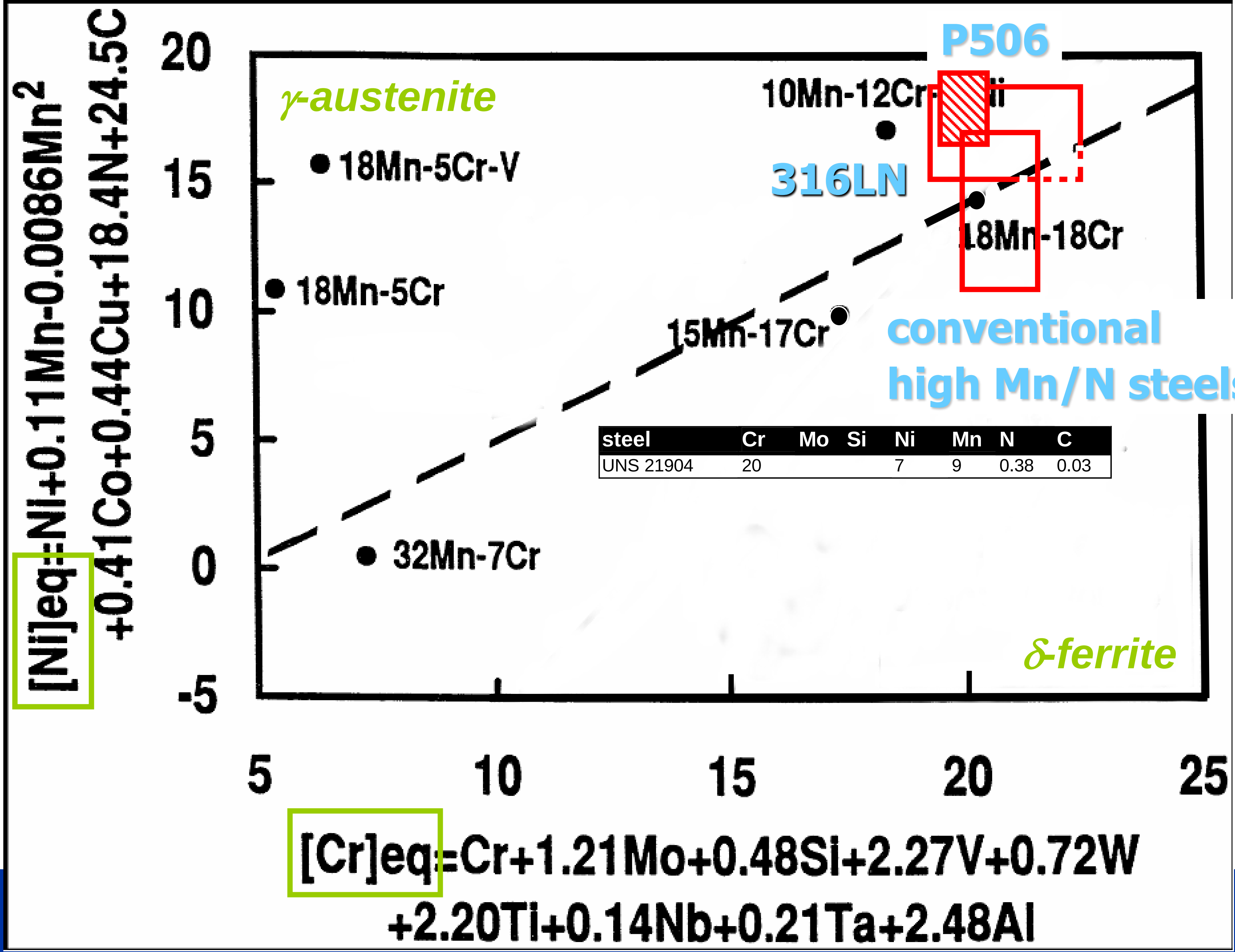






"mumetal", Ni80Mo0.5N
S<0.0005; P=0.003 (!)

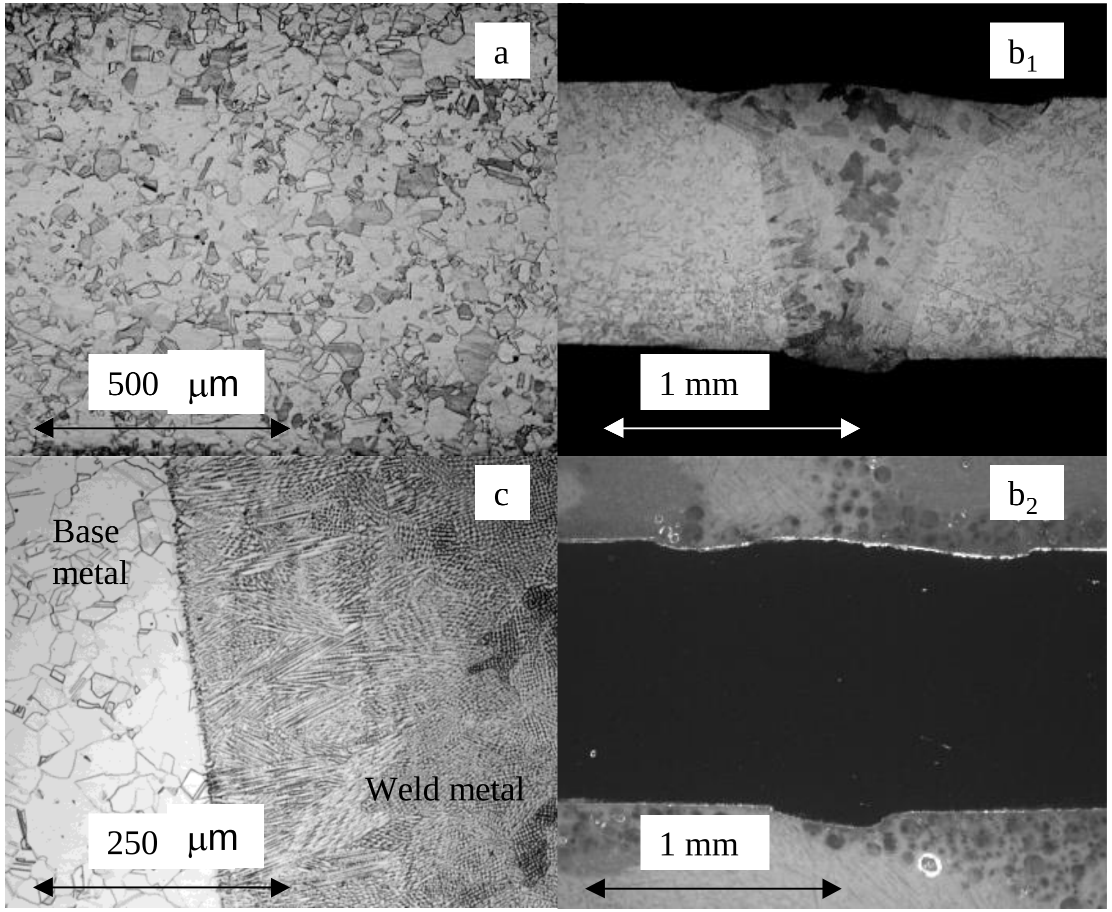
Materials for magnets: austenitic stainless steels



steel	Cr	Mo	Si	Ni	Mn	N	C
UNS 21904	20			7	9	0.38	0.03

Materials for magnets: austenitic stainless steels

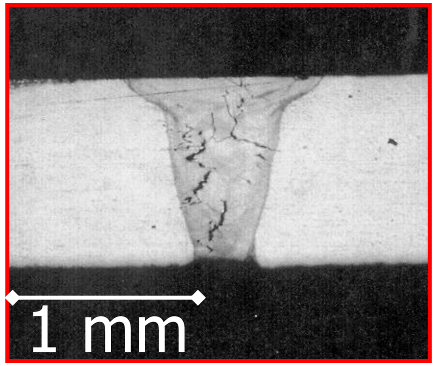
Steels	C	Mn	Ni	Cr	Mo	Si	N	P	S	B
P506	0.012	**12.05**	10.90	19.18	0.86	0.23	**0.33**	0.005	0.001	<0.001

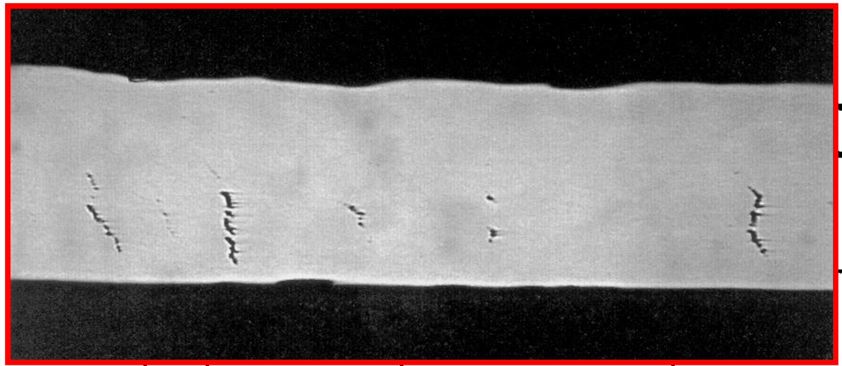


S. Sgobba, C. Boudot, Soudabilité laser d'aciers inoxydables austénitiques, Matériaux et Techniques 95, n°11-12, p. 23 (1997).

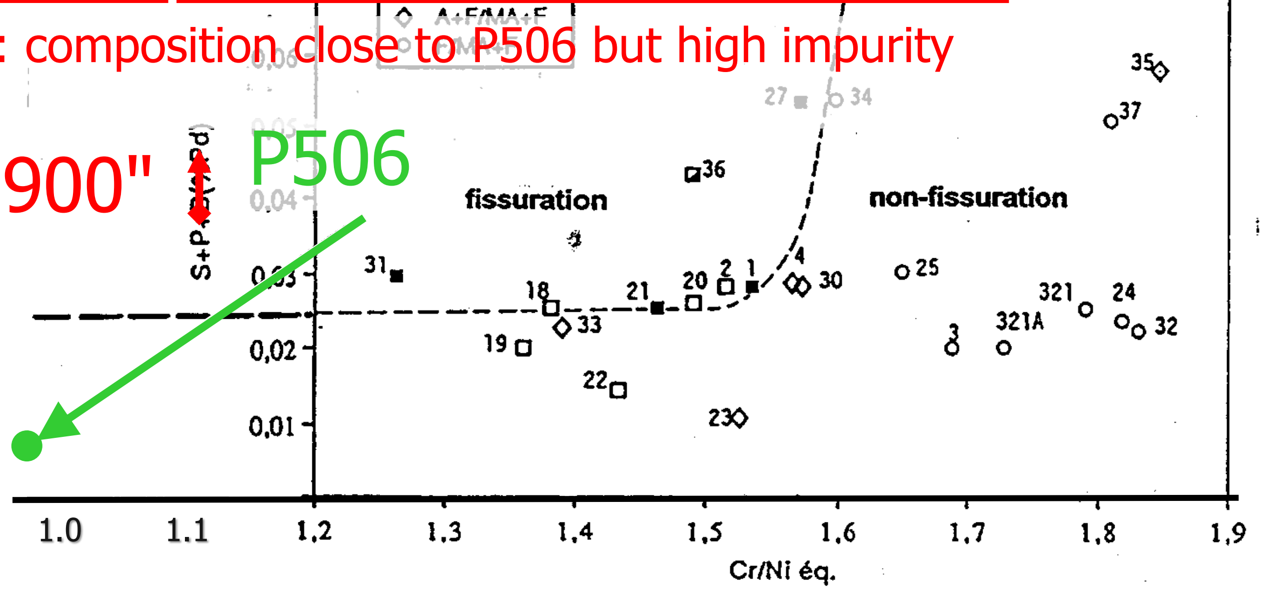
J.P. Bacher and S. Sgobba, TIG Weldability of Special Stainless Steels for the Beam Screen of the Large Hadron Collider, Bulletin du Cercle d'Etude des Métaux, XVI, p. 13.1 (1995).

Materials for magnets: austenitic stainless steels

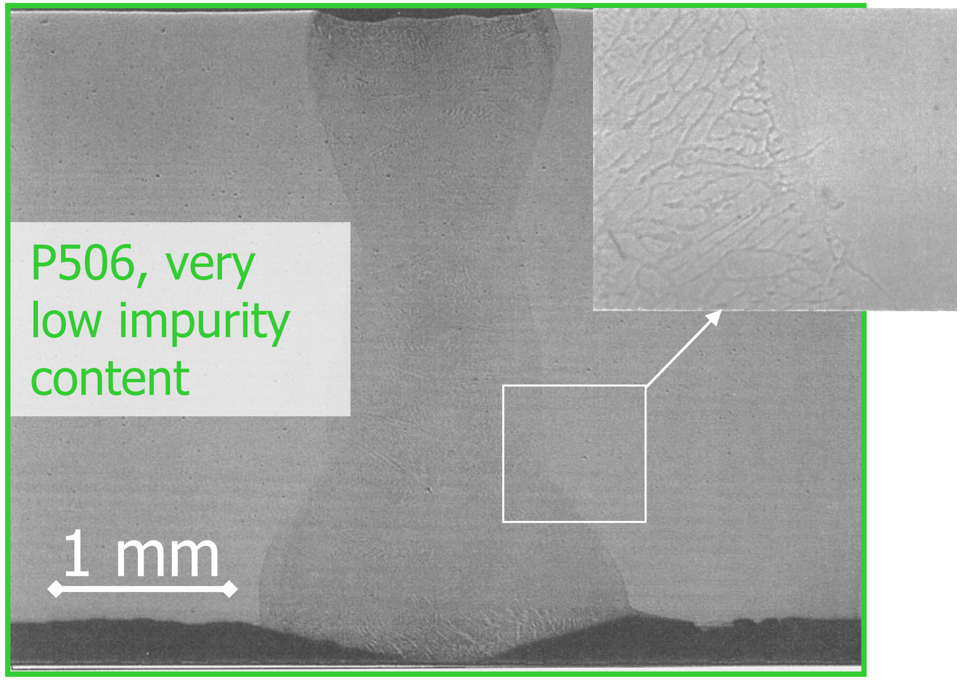




"900" steel: composition close to P506 but high impurity content

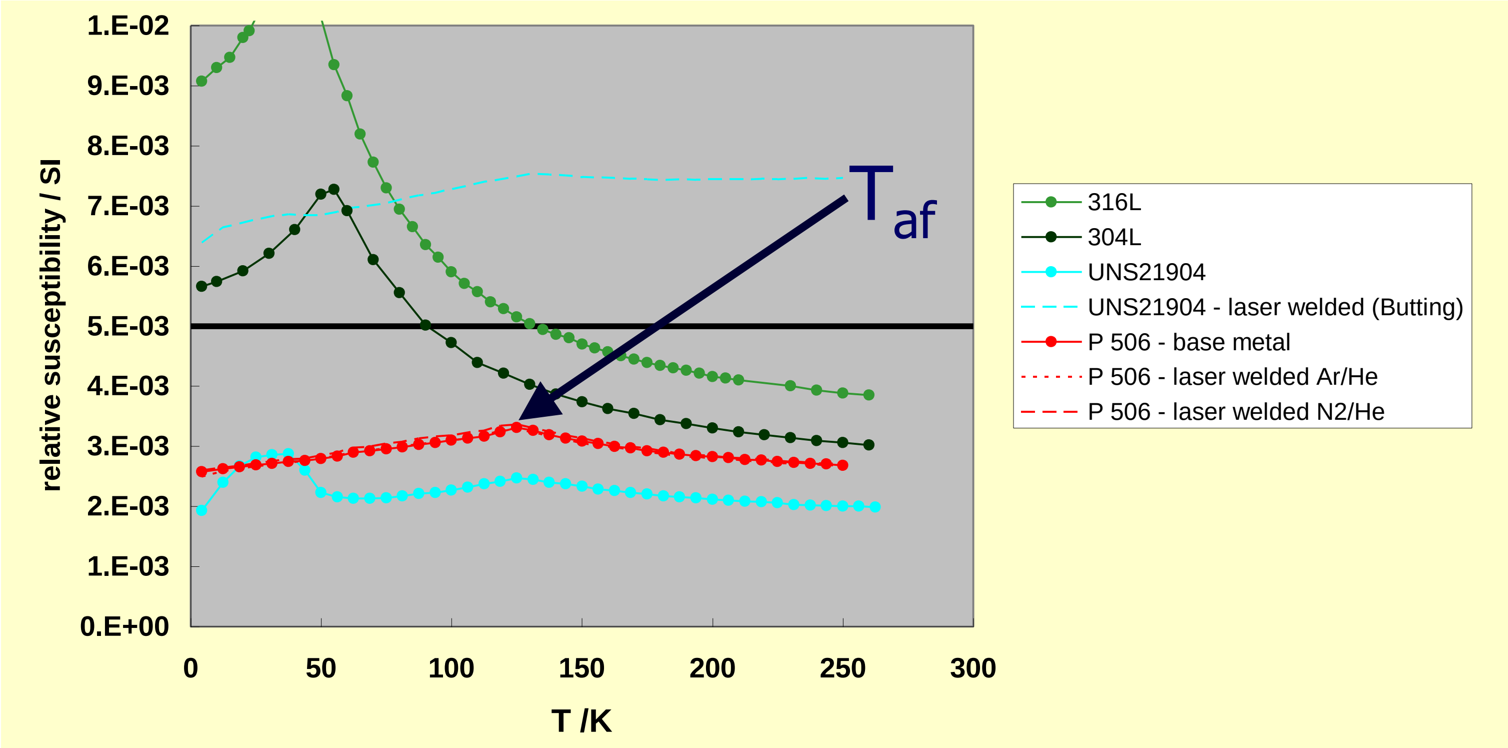


$$\frac{Cr_{éq.}}{Ni_{éq.}} = \frac{Cr + 1,37Mo + 1,5Si + 2Nb + 3Ti}{Ni + 0,31Mn + 22C + 14,2N + Cu}$$



S. Sgobba: proc. Cycle Métaux et Procédés, CIP - Tramelan /CH, 1996, p. 8/1-10

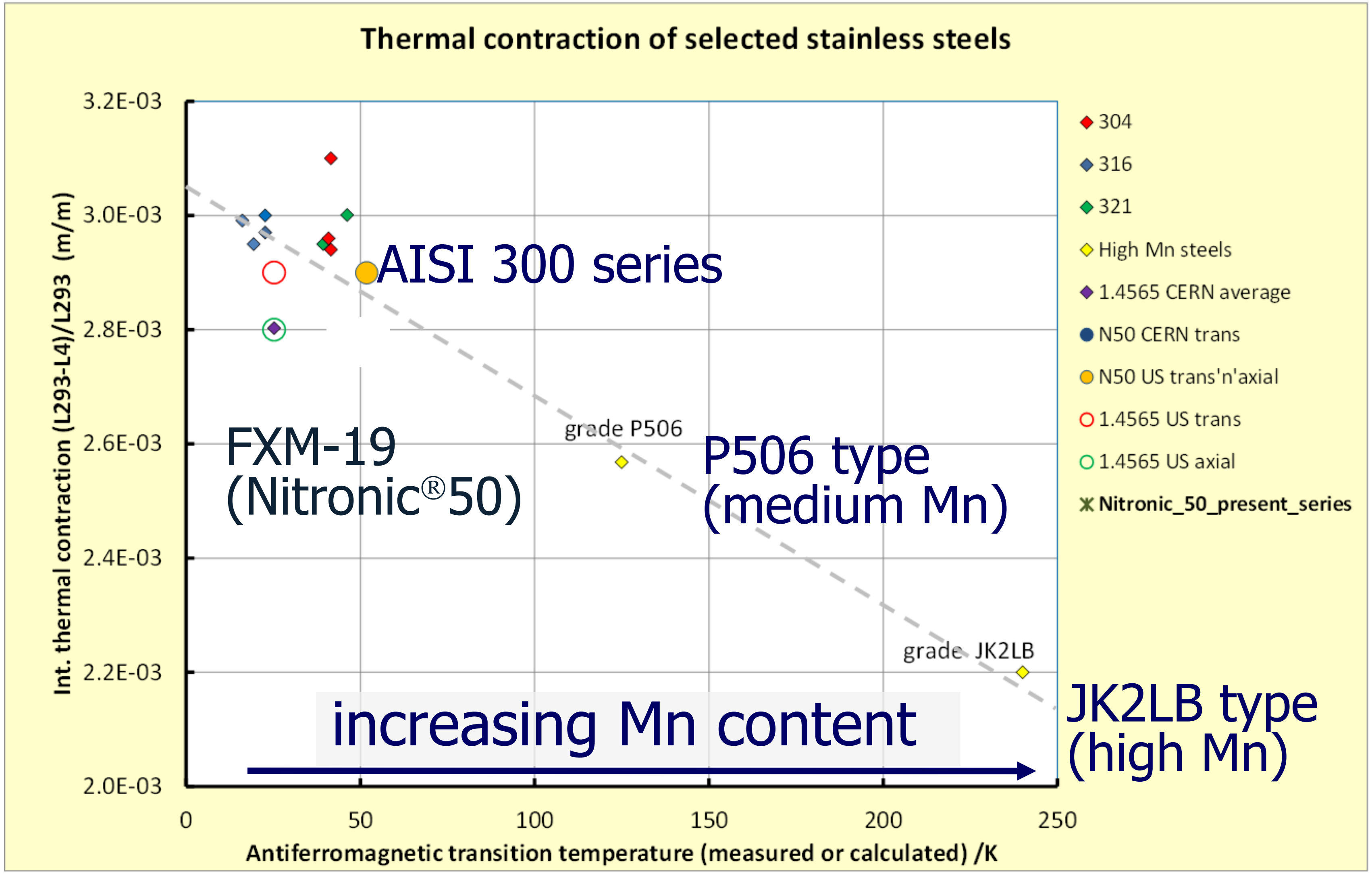
Materials for magnets: austenitic stainless steels



Warnes law: $T_{af}(K) = 90 - 1.25Cr - 2.75Ni - 5.5Mo - 14Si + 7.75Mn$

P506, predicted T_{af} = 121.5 K, measured 125.7 K

Materials for magnets: austenitic stainless steels



Courtesy of ITER, @iter.org

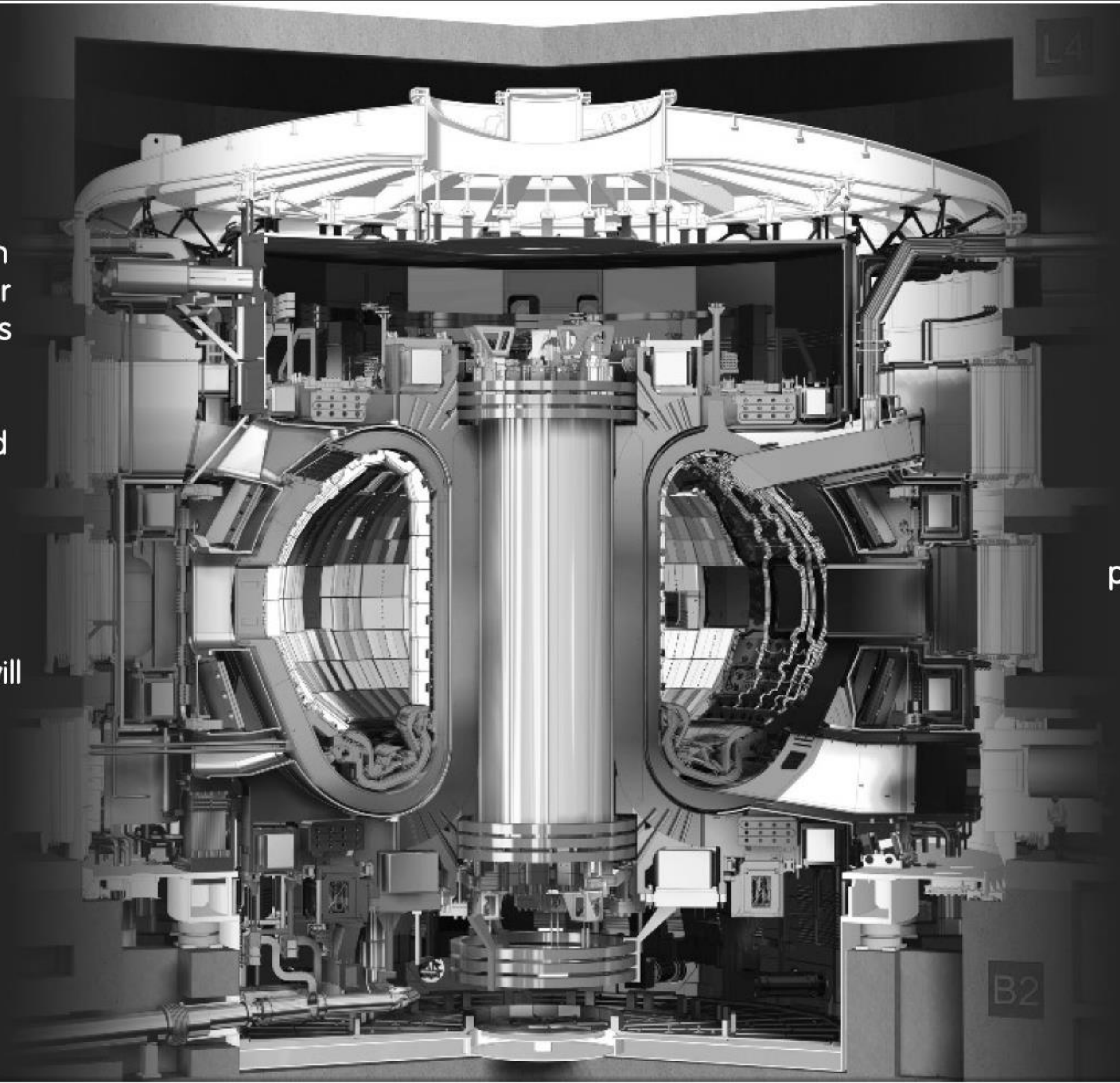
ITER TOKAMAK

AN INTERNATIONAL PROJECT FOR A NEW & CLEAN ENERGY

ITER represents the future of nuclear power where the fission reaction is replaced by a fusion reaction, the nuclear reaction that powers the sun and the stars, a safe, non-carbon emitting and virtually limitless energy.

With its millions of components, ITER will be the largest and most powerful tokamak ever built.

35 countries will collaborate during 35 years

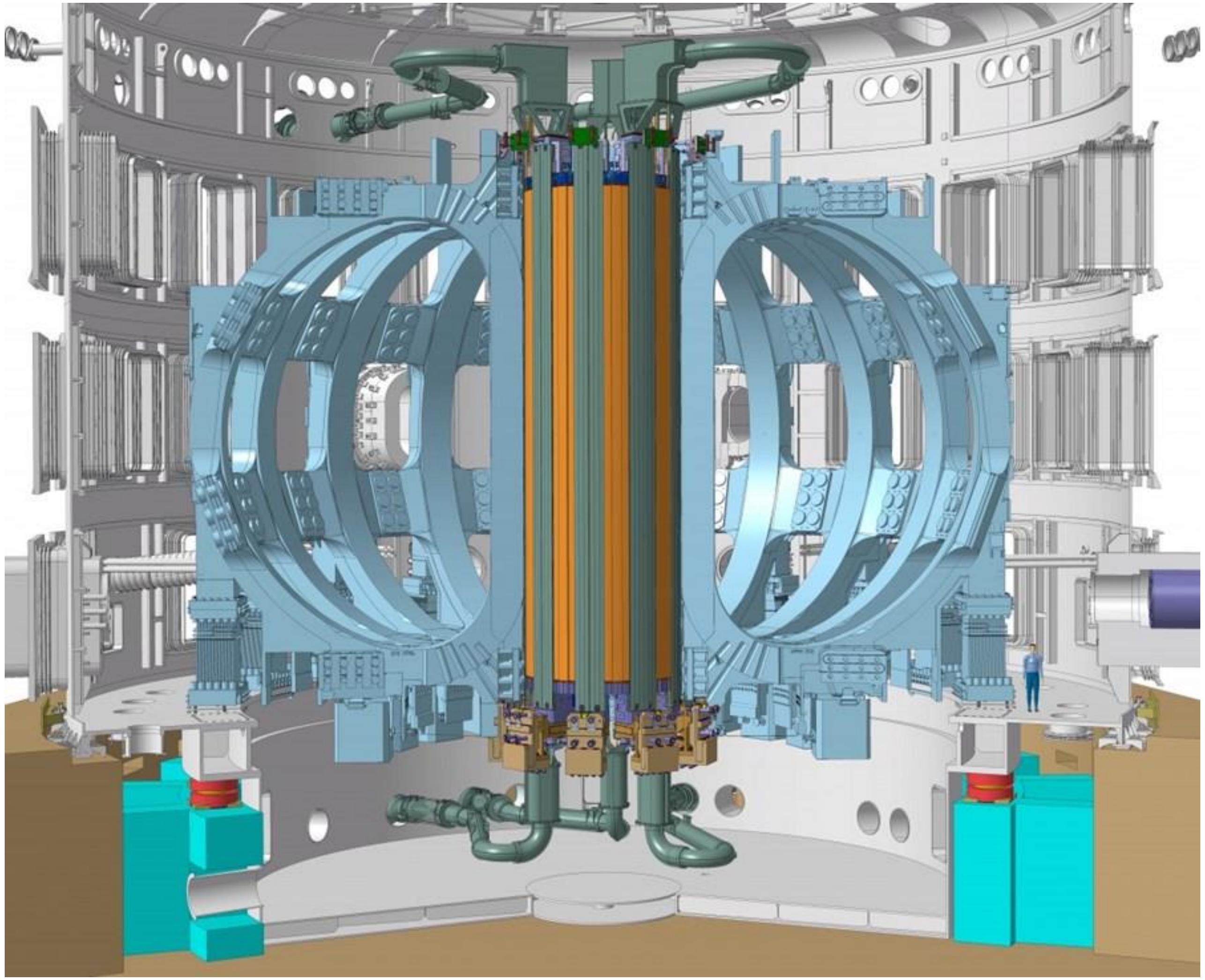


A GIANT
23 000 T

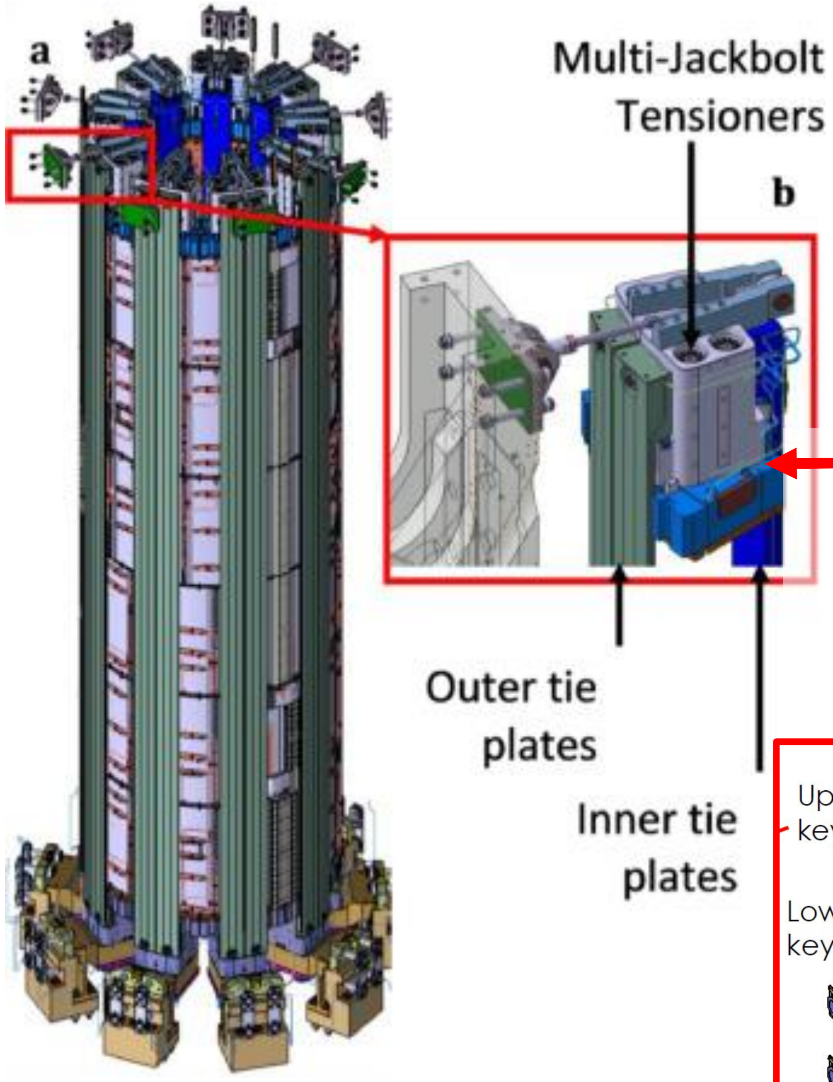
10X the core of the sun
150 milllions ° C
plasma temperature

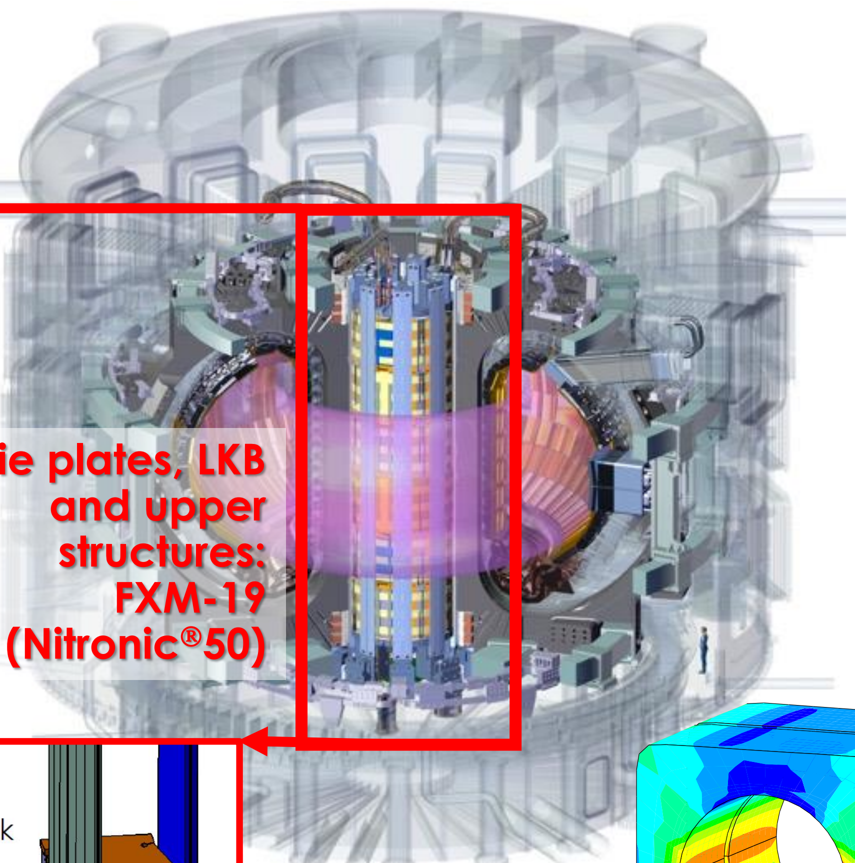
FUSION ENERGY
500 MW
Output power

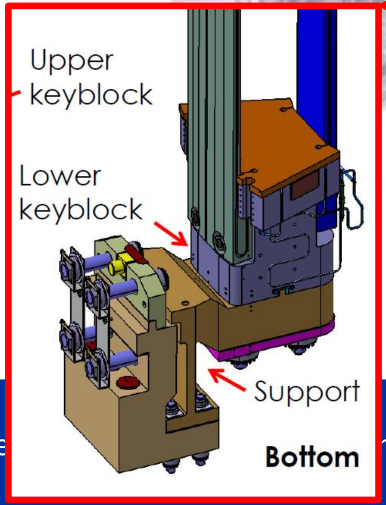
Materials for magnets: austenitic stainless steels



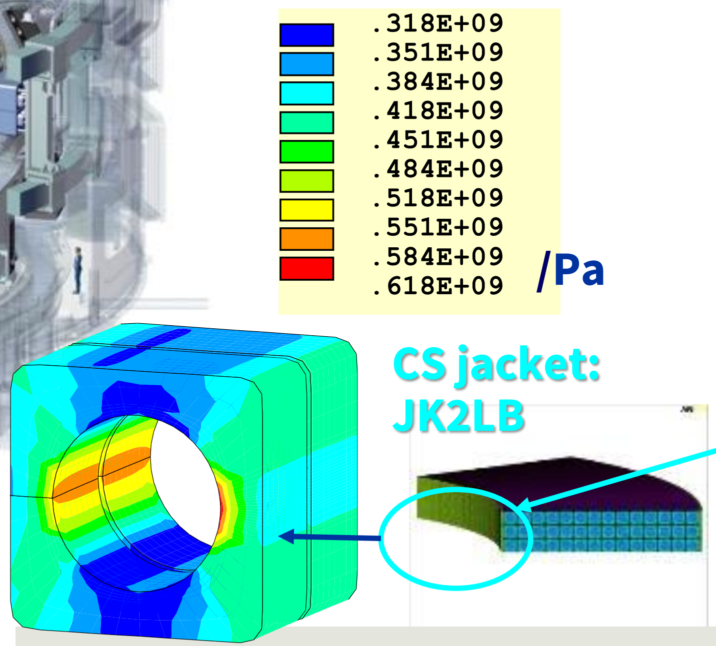
Materials for magnets: austenitic stainless steels

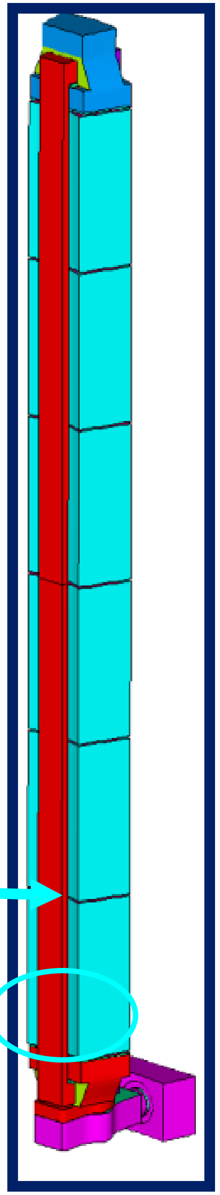






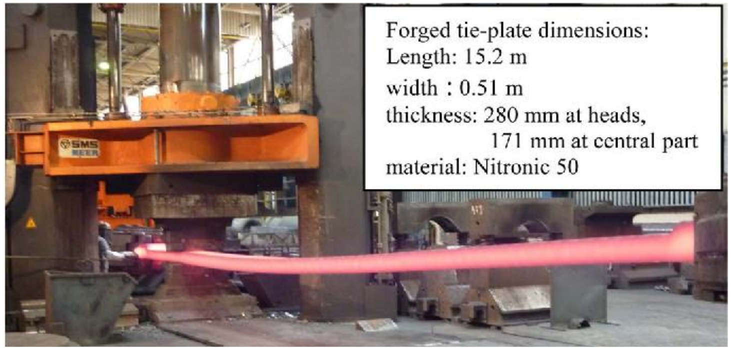
Central Solenoid Assembly Tooling Design Description, courtesy of S. Litherland, USIPO ↓





S. Sgobba et al., Metallurgical assessment of large size tensioning components for the precompression structure of the ITER central solenoid, Fusion Engineering and Design, Vol. 170, 2021, https://doi.org/10.1016/j.fusengdes.2021.112543

Materials for magnets: austenitic stainless steels



- Very large multidirectionally forged components

Tie plate single piece forging. Courtesy of Rolf Kind GmbH

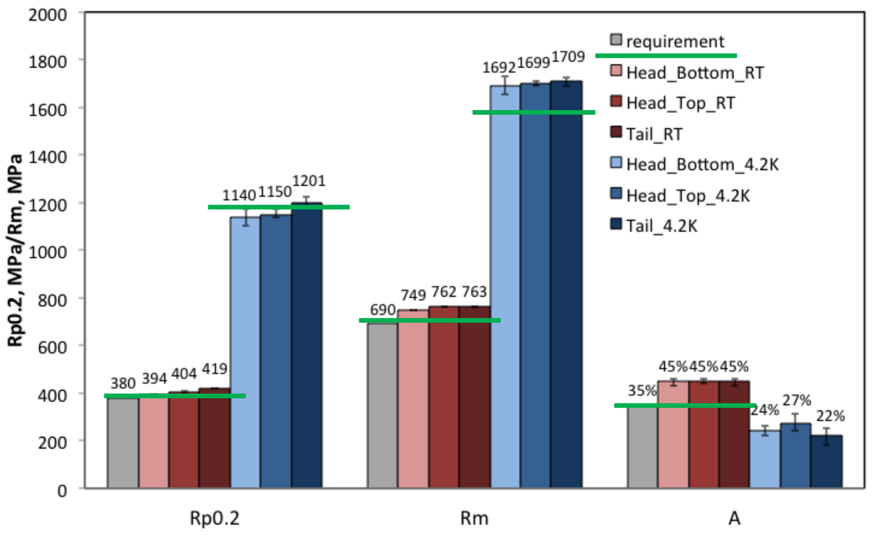
Lower Support brackets: from material specification to 100% volumetric inspection. Courtesy of Monchieri

Lower key block in test assembly. Courtesy of US ITER and Petersen Inc.

Materials for magnets: austenitic stainless steels

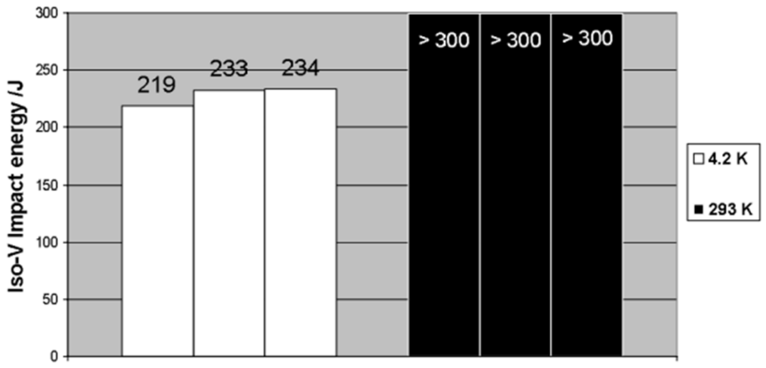
Mechanical properties

FXM-19



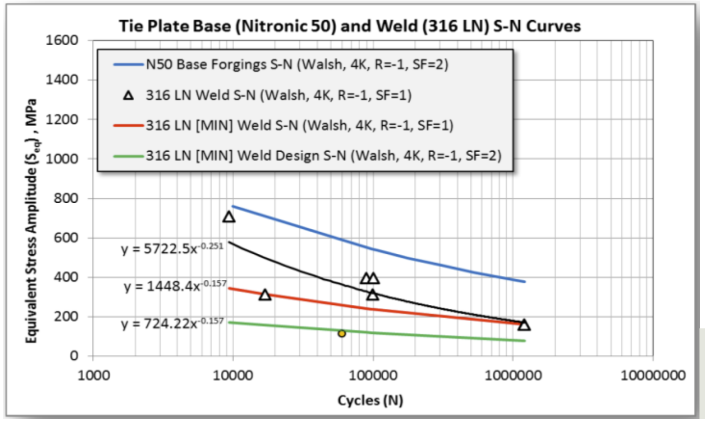
S.A.E. Langeslag et al., "Extensive Characterisation of Advanced Manufacturing Solutions for the ITER Central Solenoid Pre-compression System," Fusion Eng. Des. (2015), https://doi.org/10.1016/j.fusengdes.2015.06.007

Temperature [K]	direction	$\sigma_{y0.2}$ [MPa]	σ_r [MPa]	ε_r [%]
293	Long.	450 ± 10	835 ± 20	61 ± 3
	Transv.	440 ± 10	825 ± 5	45 ± 4
77	Long.	1180 ± 10	1760 ± 20	57 ± 4
	Transv.	1120 ± 50	1715 ± 100	45 ± 3
4.2	Long.	1620 ± 50	2115 ± 60	18 ± 3
	Transv.	1700 ± 100	2105 ± 90	15 ± 4



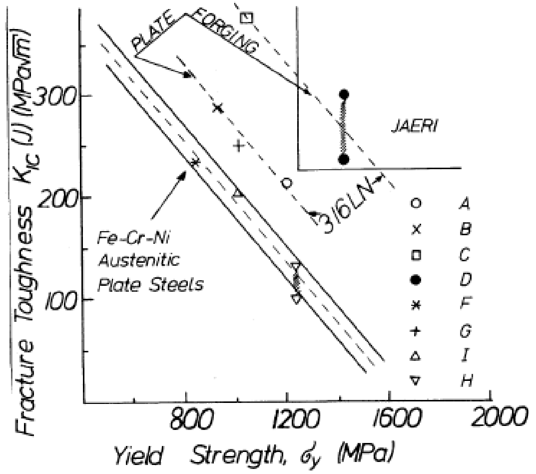
P506

	Specimen location	Specimen orientation	K_{IC} [MPa√m]	J_{IC} [N/mm]
Single piece forged	Head (top)	LT	170	130
	Head (bottom)	LT	190	161
		LS	197	172
	Tail (slab)	LT	188	157
		LT	226	239
Welded solution	weld	weld direction	112	62



Courtesy of R.P. Walsh, NHMFL

Materials for magnets: austenitic stainless steels



4 K toughness-strength relation of nitrogen strengthened stainless steels.

A. Nyilas, P. Komarek - Cryogenic Tensile and Fracture Properties of Structural Materials for Superconducting Magnets in Fusion Technology (1989)

Courtesy Dr. N. Pauze, ArcelorMittal Industeel

Nuclear physics & Fusion research

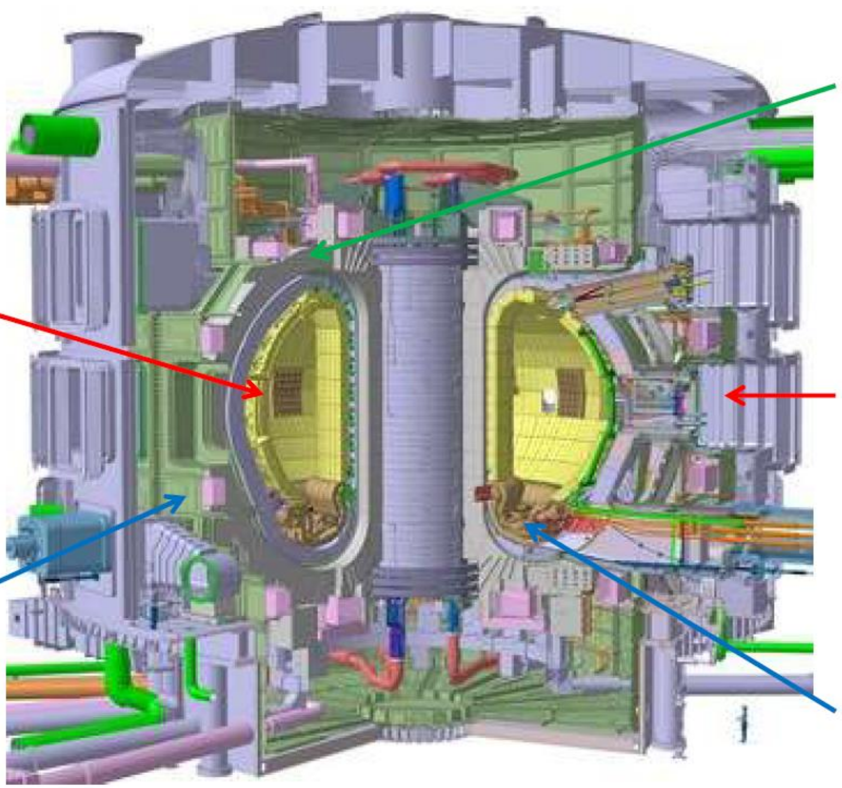
ArcelorMittal

ITER PROJECT SUMMARY

VV, IWS, Ports & Components, Port plugs
HHI, Efremov, Iter India, AMW, ENSA,CNIM-LNT
316L(N)-IG,
304/304L,
304B4,
430
7300T

TFCoil (CP and TFCS)
MHI, TOSHIBA, CNIM
316LNH
1200T

CRYOSTAT:
LNT
304L Iter
2500T



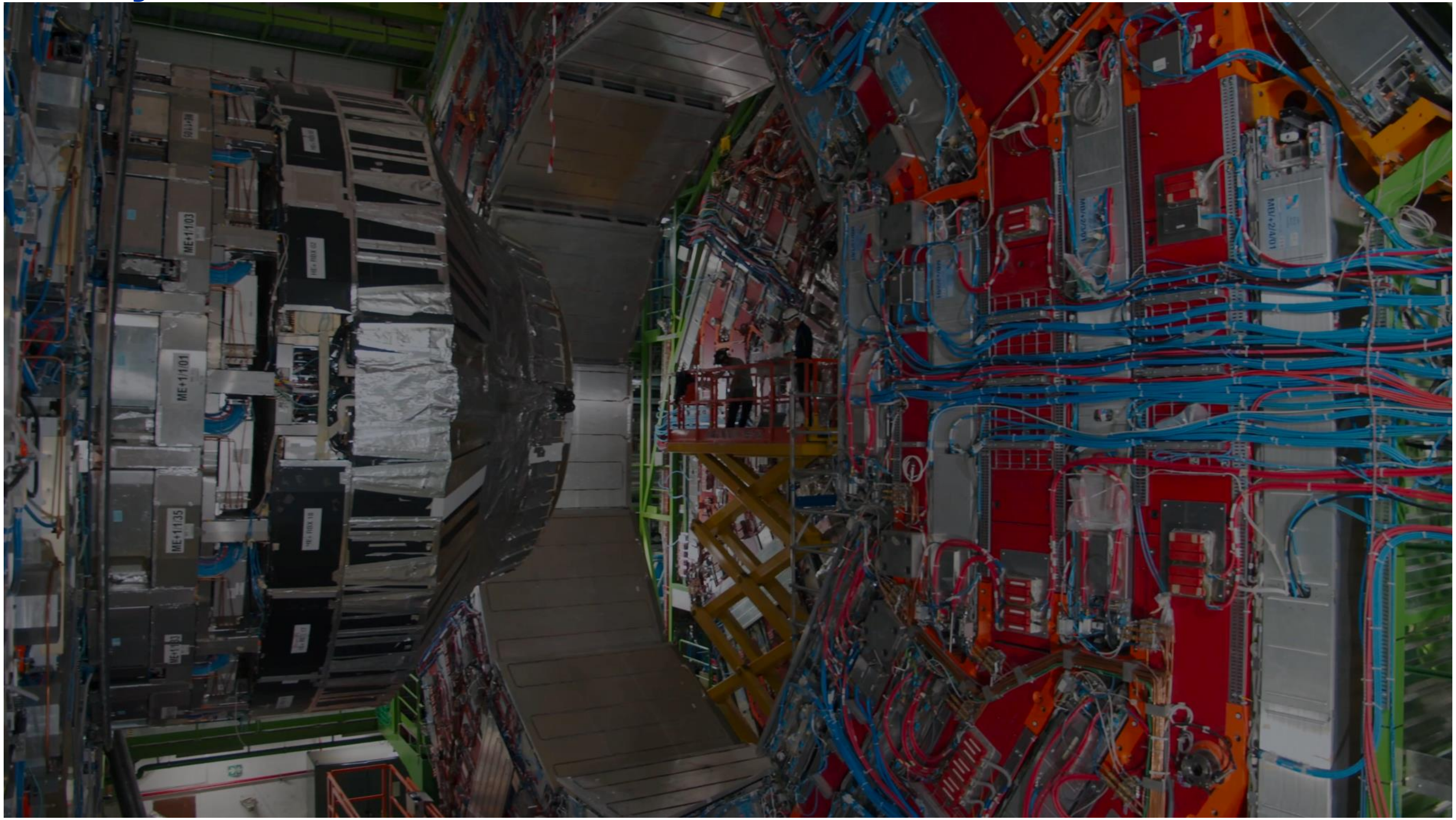
THERMAL SHIELD:
SFA
304LN
1700T

DIVERTOR:
Hollming, CNIM, Walter Tosto
316L(N)-IG
20T

> 12 500T booked

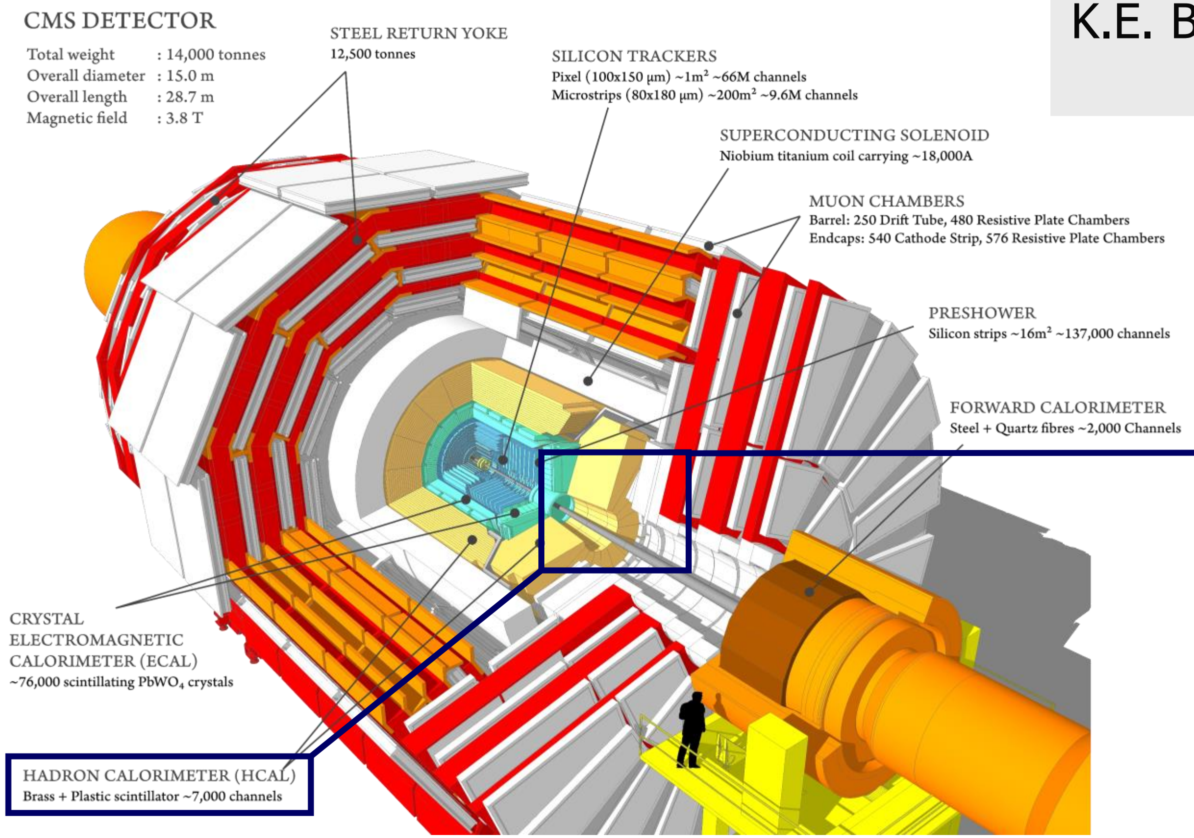
8

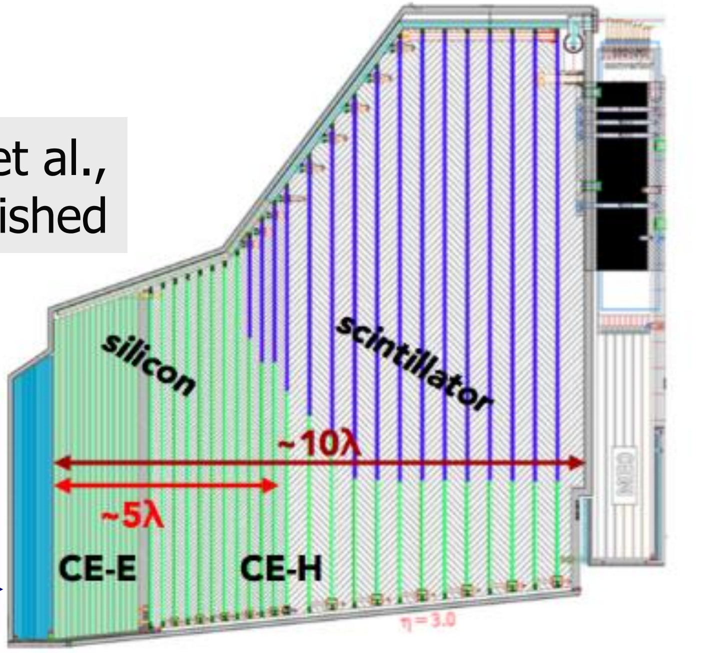
Materials for magnets: case study. Austenitic stainless steels: a low permeability steel for the new CMS HG-CAL detector



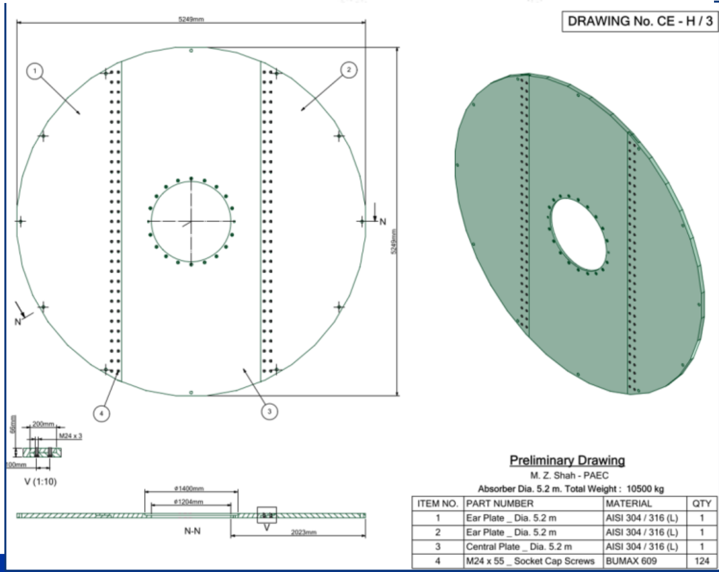
Case study: a low permeability steel for CMS HG-CAL

K.E. Buchanan, S. Sgobba et al., to be published





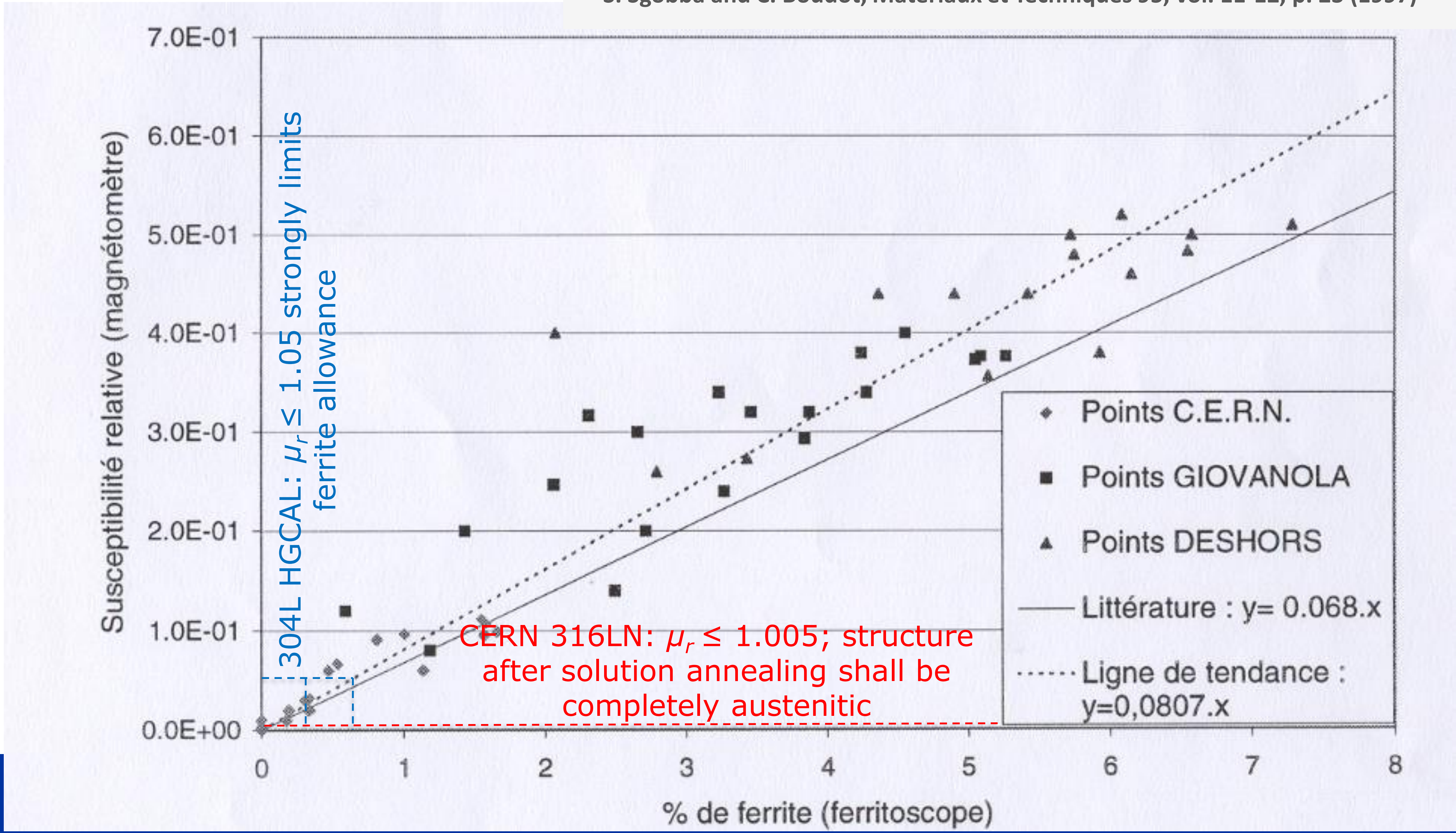
Schematic view of the High Granularity Calorimeter



- 564 t of stainless steel required for the CE-H cassettes, thickness 45 ~110 mm
- The relative magnetic permeability in the bulk plate material shall not exceed **1.05**
  - Stringent control of ferrite content
  - Stability against martensitic transformations

Case study: a low permeability steel for CMS HG-CAL

S. Sgobba and C. Boudot, Matériaux et Techniques 95, vol. 11-12, p. 23 (1997)



Case study: a low permeability steel for CMS HG-CAL

Nuance - Grade - Werkstoff	
	X5CrNi18-10 (1.4301)
	X5CrNi18-10 (1.4301)
	UNS S30400 (304)
	UNS S30403 (304L)
	UNS S30400 (304)
	UNS S30403 (304L)
	X2CrNi19-11 (1.4306)
	X2CrNi19-11 (1.4306)

Etat thermique de livraison - Heat treatment state of delivery - Wärmebehandlung Lieferzustand
Hypertrempe eau (1050 °C - 0.5 min/mm) - Solution annealed and water quenched
Procédé d'élaboration - Melting process - Erschmelzungsart
Electric-arc furnace - VOD - Finish n°1 - 1D - HRAP

NUMERICAL DESIGNATION
1.4306

Material designation:
X2CrNi19-11
Country/Standard:
European Union / EN
Group of Materials:
Metals
Subgroup:
EN 10028-7 Flat products made of steels for pressure purposes - Part 7: Stainless steels
Comment:
Austenitic stainless steel

Courtesy of S. Moccia & M. Pentella /CERN EP

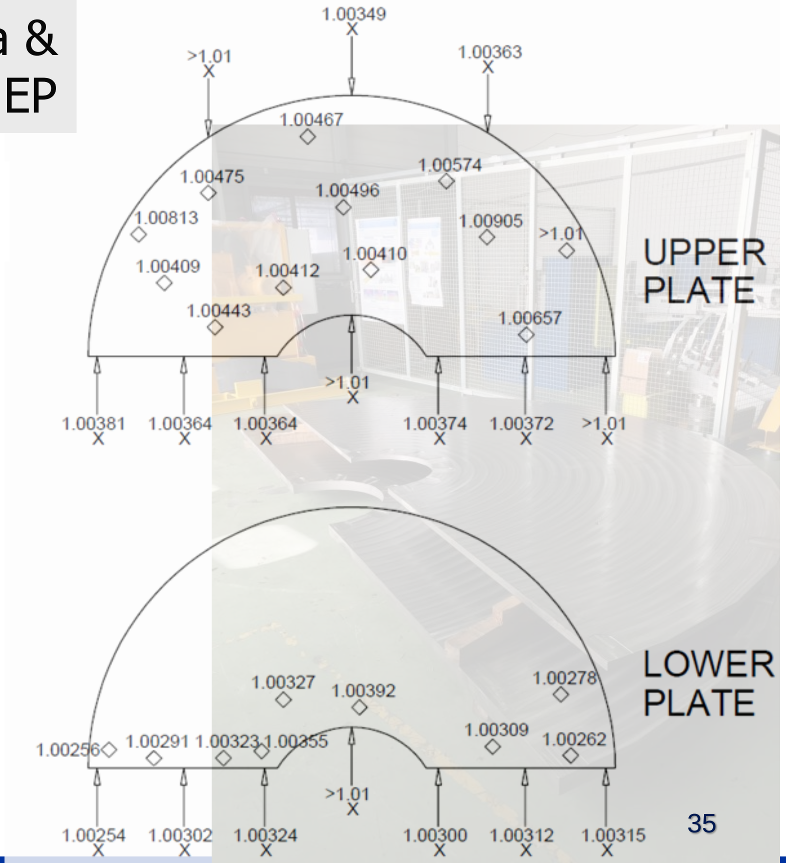
ArcelorMittal Industeel

Very clean heat, 143 ppm S+P

"High alloy" 1.4306, Ni 10.417 %

1.4306: "High alloy" 304L

Criteria	Min.	Max.	Approx
C		0.03	
Mn		2.00	
P		0.045	
S		0.015	
Si		1.00	
Ni	10.0	12.0	
Cr	18.0	20.0	
N		0.10	



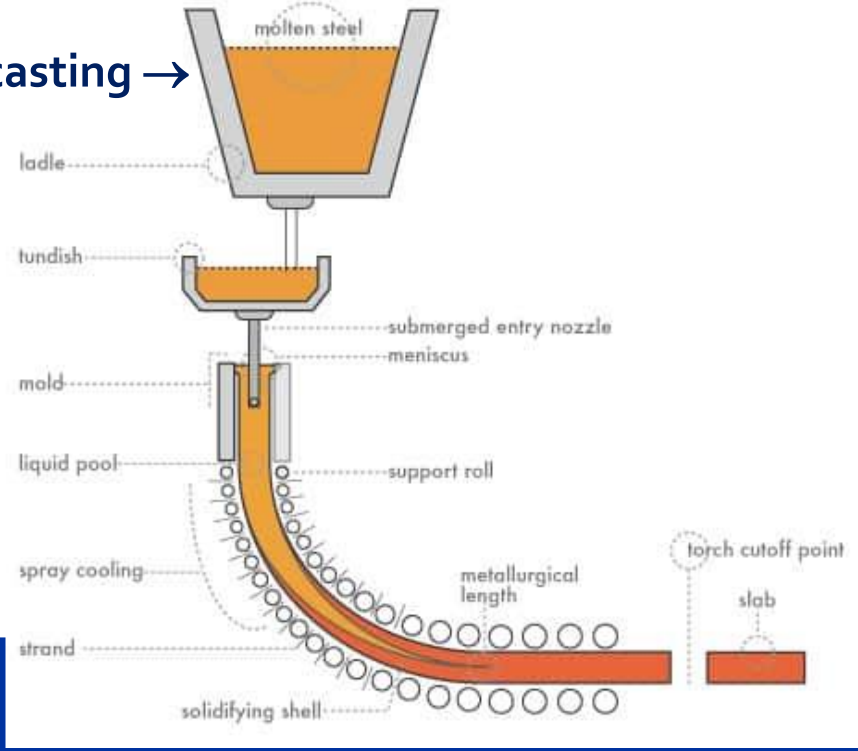
- Low magnetic permeability:
  - Stringent control of ferrite content (composition / steelmaking route)
  - Stability against martensitic transformations (grade selection)

← Ingot casting →

Rolled slab

Rolling of quarto plates

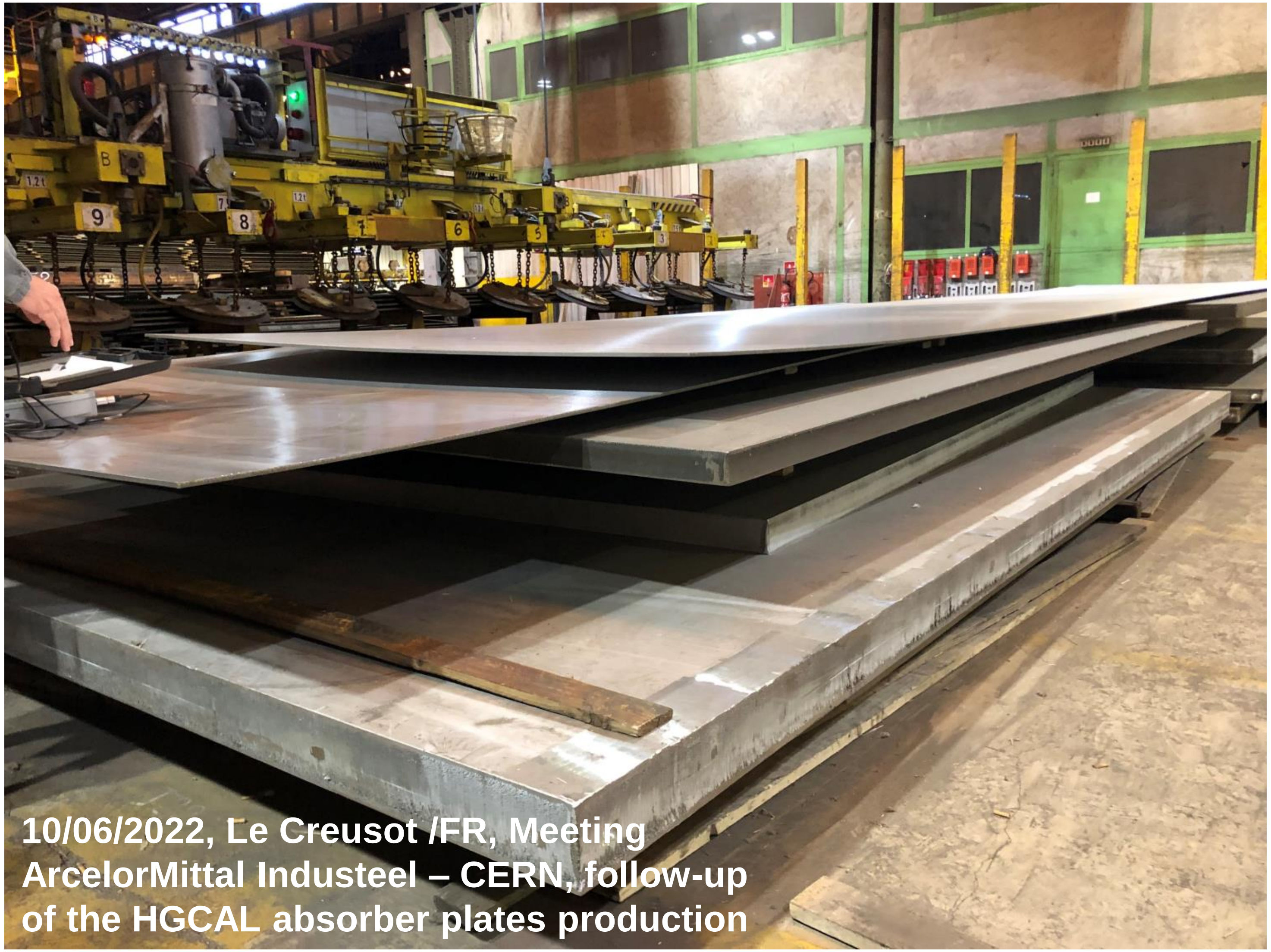
Versus continuous casting →



Solution annealing and finishing (descaling, grinding, skin pass rolling where applicable)

Case study: a low permeability steel for CMS HG-CAL

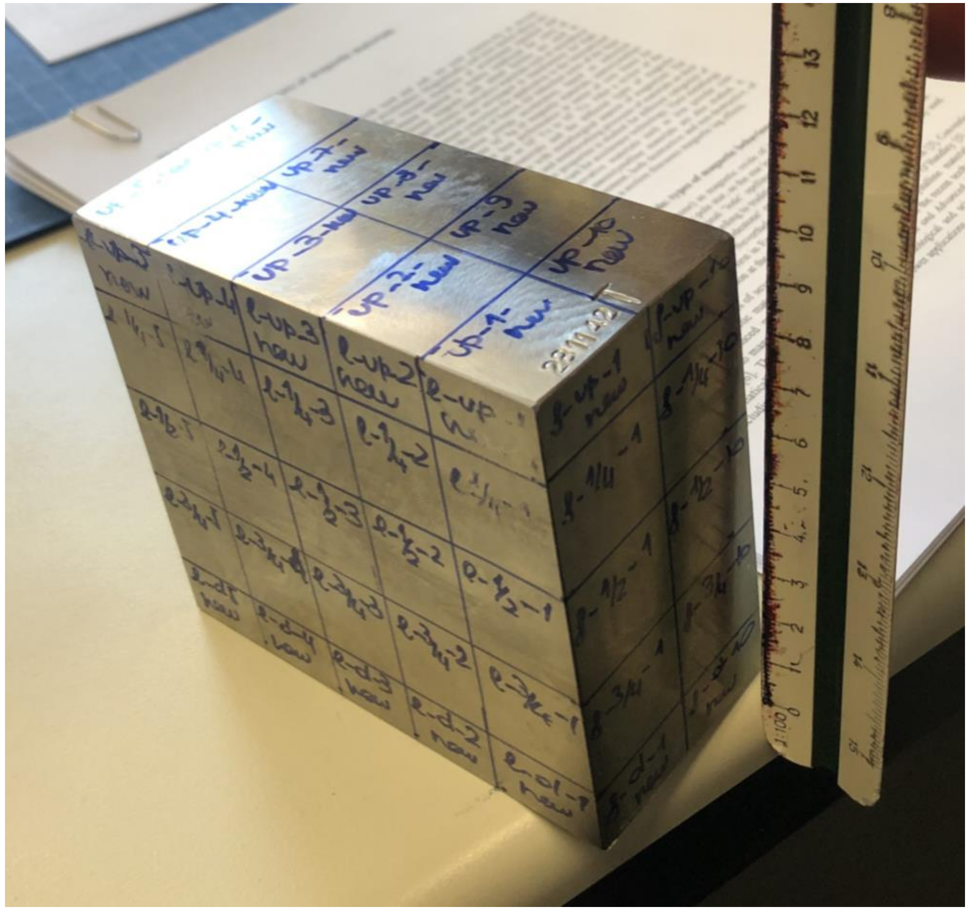
ArcelorMittal Industeel



10/06/2022, Le Creusot /FR, Meeting ArcelorMittal Industeel – CERN, follow-up of the HGCAL absorber plates production

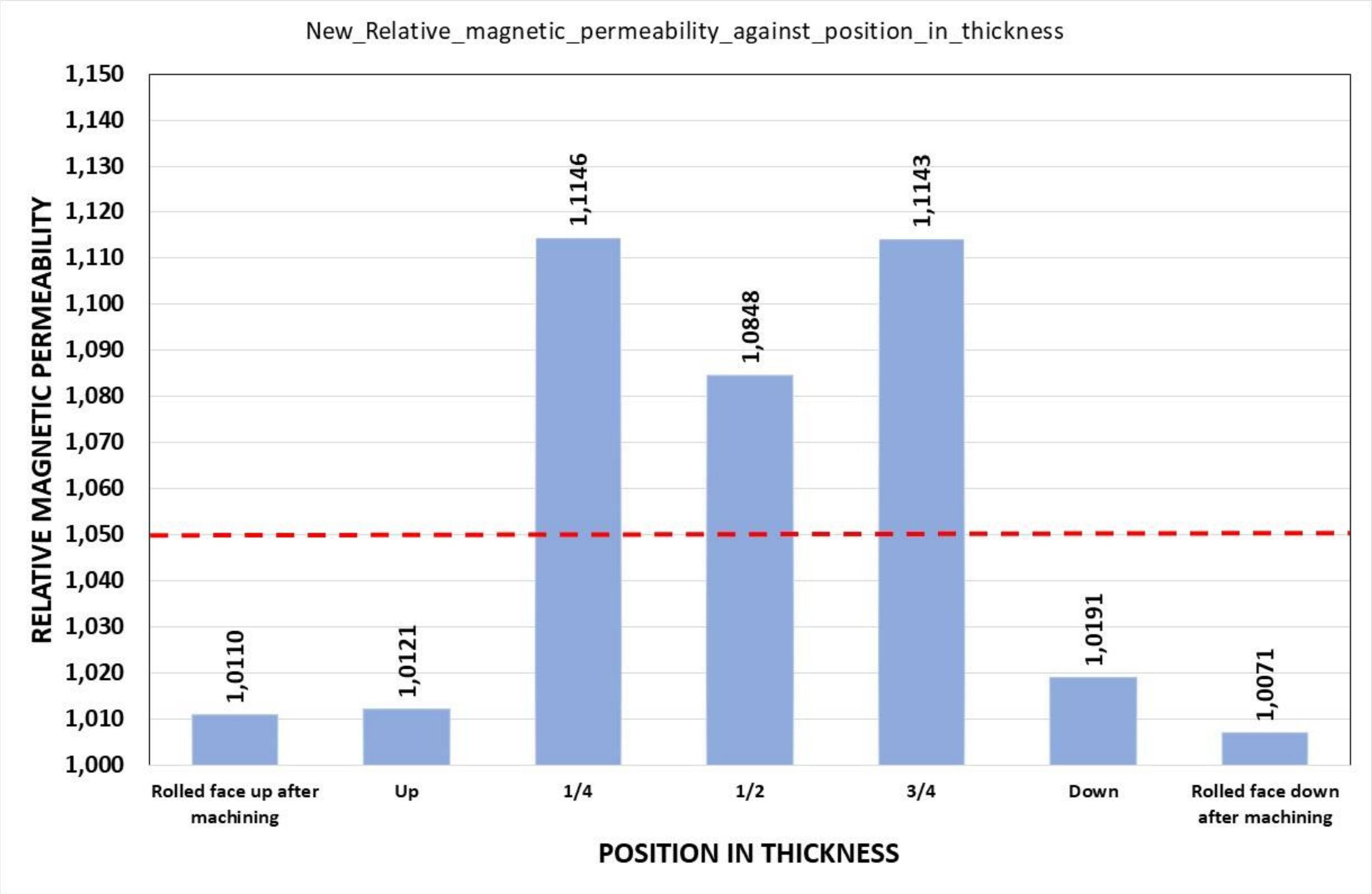
Case study: a low permeability steel for CMS HG-CAL

Quartering of a sample issued from a 120 mm plate



- This sample was issued from a 120 mm thick plate and symmetrically machined down to 100 mm
- Other dimensions unchanged (50 mm x 100 mm)
- This machining operation is representative of the fabrication of the HGCAL plates, whose thickness will be reduced with respect to the original as-rolled thickness

Case study: a low permeability steel for CMS HG-CAL



- Double peak around mid-thickness (at ¼ *t* and ¾ *t*, respectively) as metallurgically expected
- The three central layers feature values above 1.05

- Average of layers in thickness, including rolled faces:
  μ_r = 1.0519
- Excluding rolled faces:
  μ_r = 1.0690

Case study: a low permeability steel for CMS HG-CAL

Double peak metallurgically expected

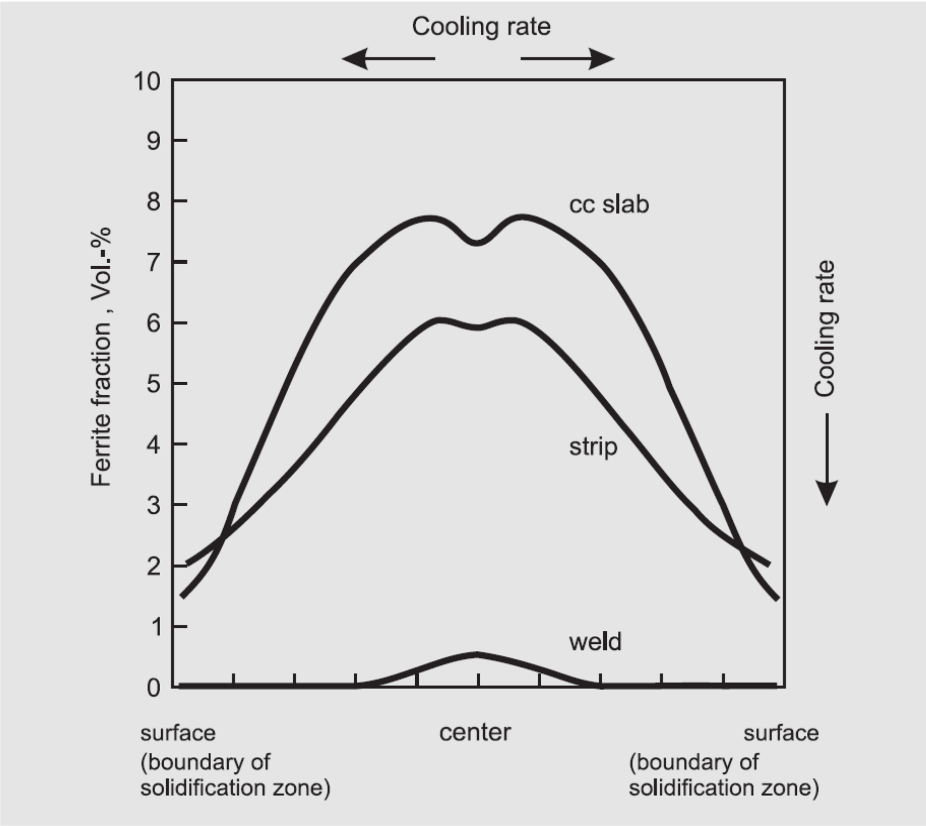
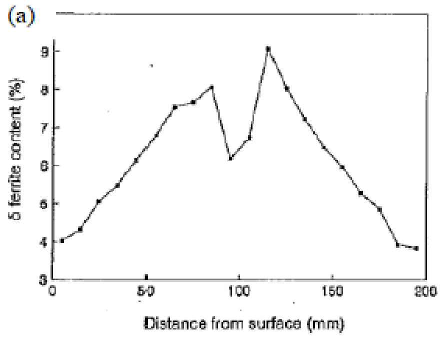
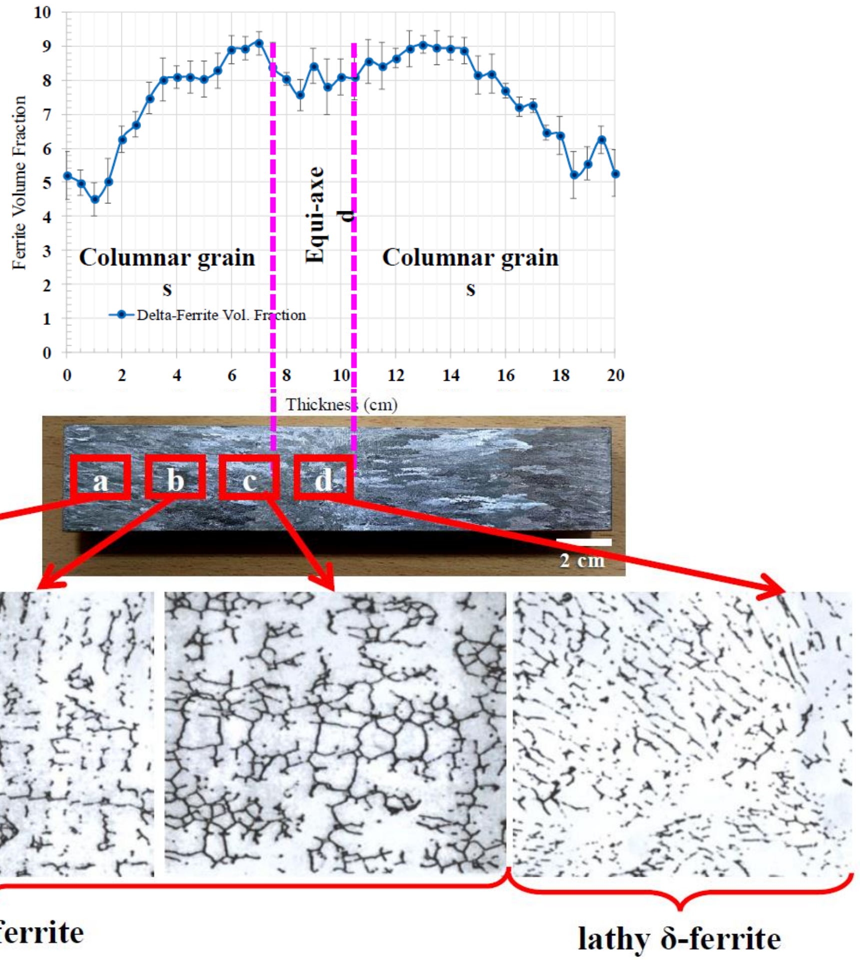


Fig. 1. Typical distribution of δ-ferrite across the solidification cross section.

From Piotr R. Scheller, Roman Flesch and Wolfgang Bleck, *Solidification Morphology and Microstructure Properties at Increased Cooling Rates for 18-8 Cr±Ni Stainless Steel, ADVANCED ENGINEERING MATERIALS 1999, 1, No. 3±4, p. 209ff.*

From S. Kim, Y. Shin, N. Kim, Distribution of δ ferrite content in continuously cast type 304 stainless steel slabs, Ironmak. Steelmak. 22 (1995) 316–325



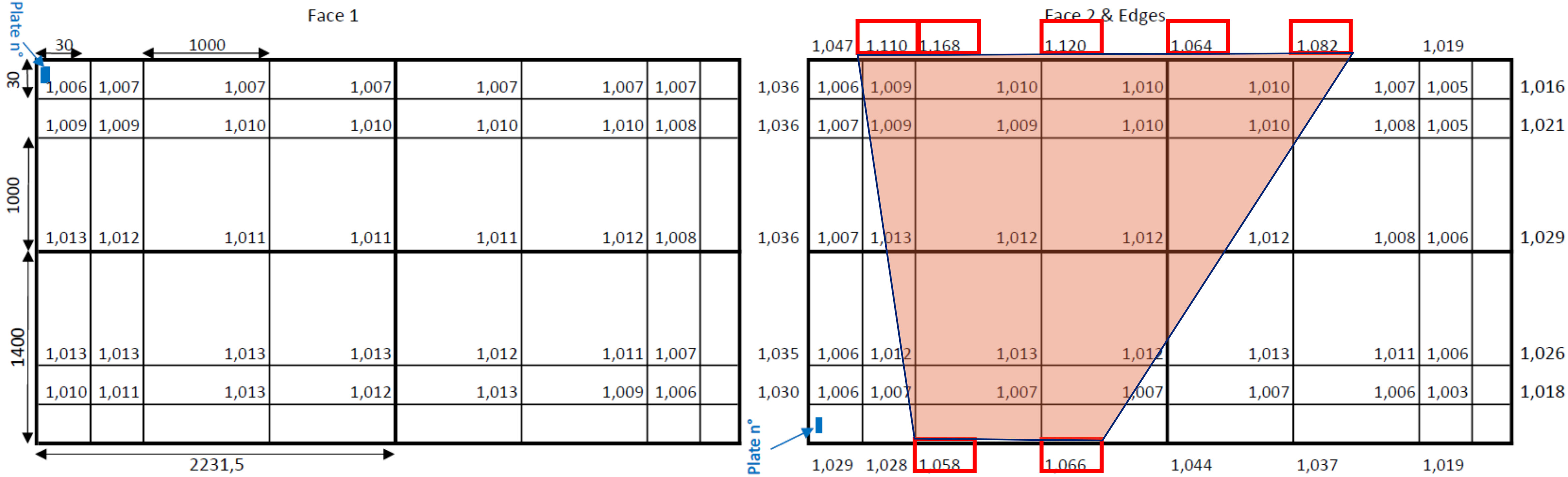


Case study: a low permeability steel for CMS HG-CAL

ArcelorMittal Industeel

ArcelorMittal Industeel results on this 60 mm plate

MAGNETIC PERMEABILITY QUARTERING 1000 X 1000					
OPERATOR :	RADOUANE RIAHI		DATE :		29/04/2022
CUSTOMER	CERN		PLATE :		281146.11
ORDER :	5301588/150		HEAT :		A220902
GRADE :	472BC - X2CrNi19–11 (1.4306)		SIZE :		60 X 2800 X 4463
Mini :	1,003	Maxi :	1,168	Average :	1,019

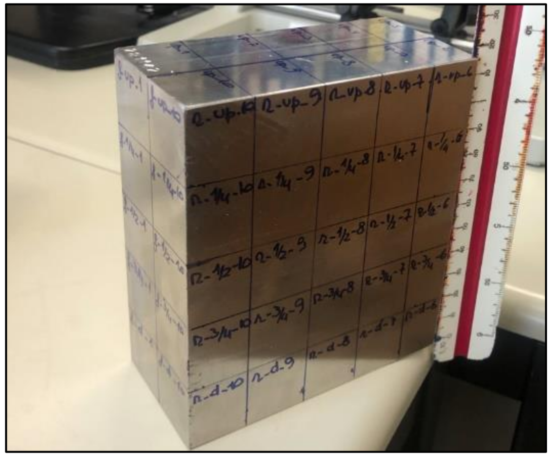


Case study: a low permeability steel for CMS HG-CAL

ArcelorMittal Industeel

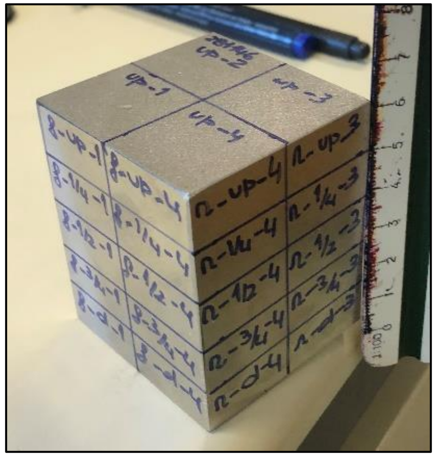
- **Volumetric measurements** through static-sample magnetometry
- All the measurements were performed using the Foerster Magnetoscop 1.069 and **a Static-Sample Magnetometer (SSM)**

Specimen #1



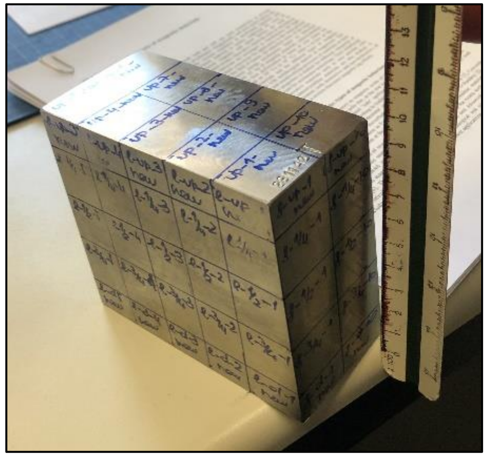
120 mm x 50 mm x 100 mm

Specimen #2



60 mm x 48 mm x 48 mm

Specimen #1 after machining

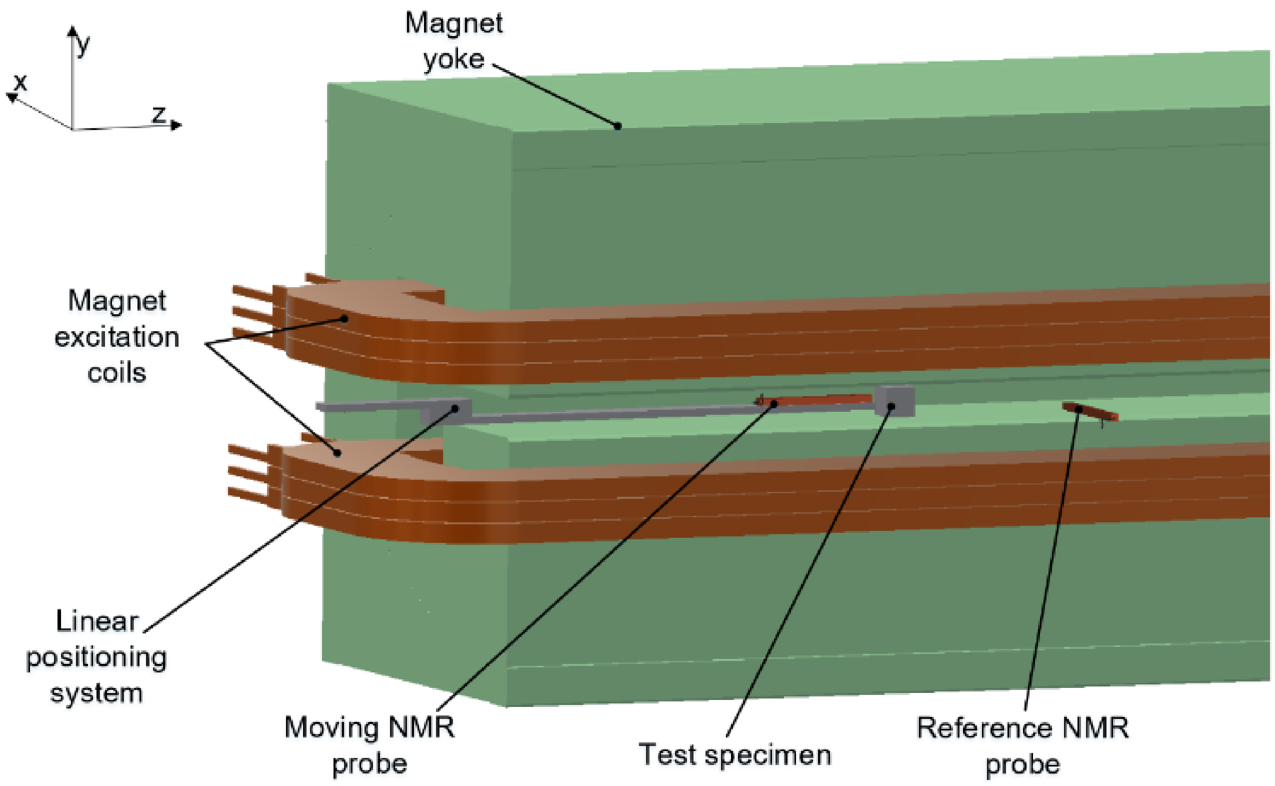


100 mm x 50 mm x 100 mm

- A second goal is to **establish a valid measurement method** for **in-situ inspection** of the absorber plates using the Foerster localised measurements

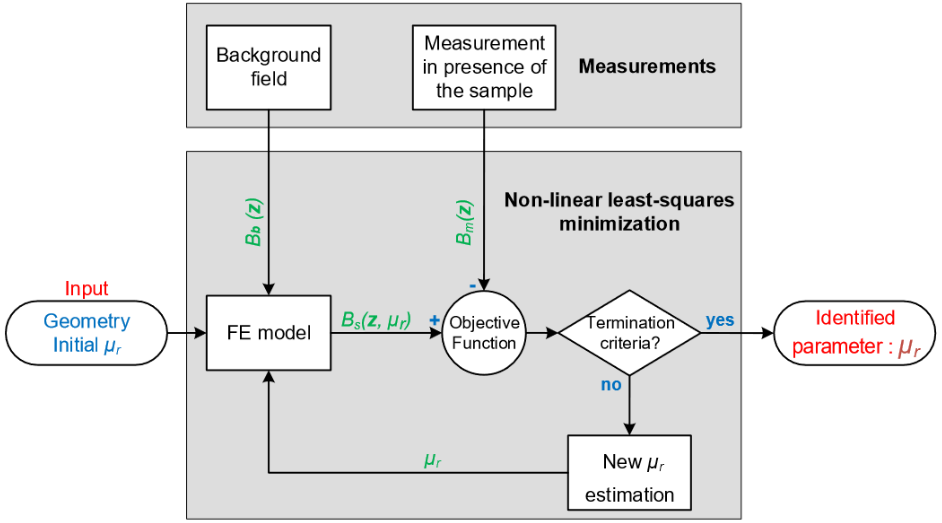
Case study: a low permeability steel for CMS HG-CAL

- The **SSM** works on the same principle of the Foerster Magnetoscop 1.069 (**flux-distortion detection**)



Measurement system layout

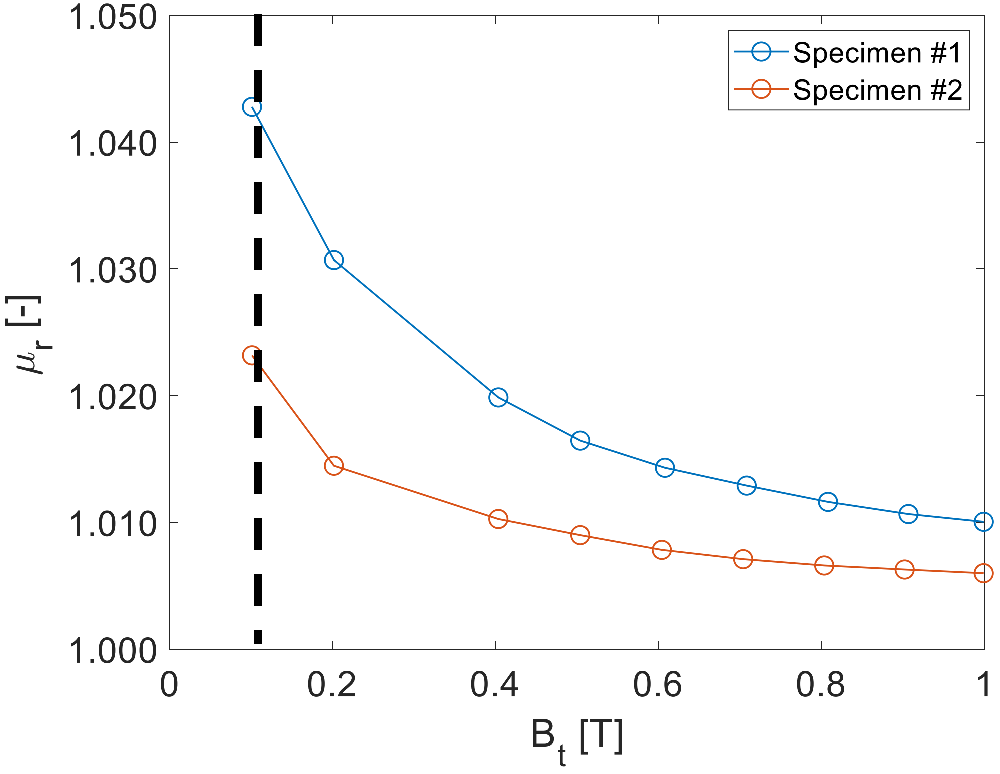
- The presence of the specimen with susceptibility ≠ 0 inside a magnetic field determines a **distortion of the field lines**
- By mapping the **background field** (no specimen) and the **distorted field**, the permeability can be computed by inverse-problem solving

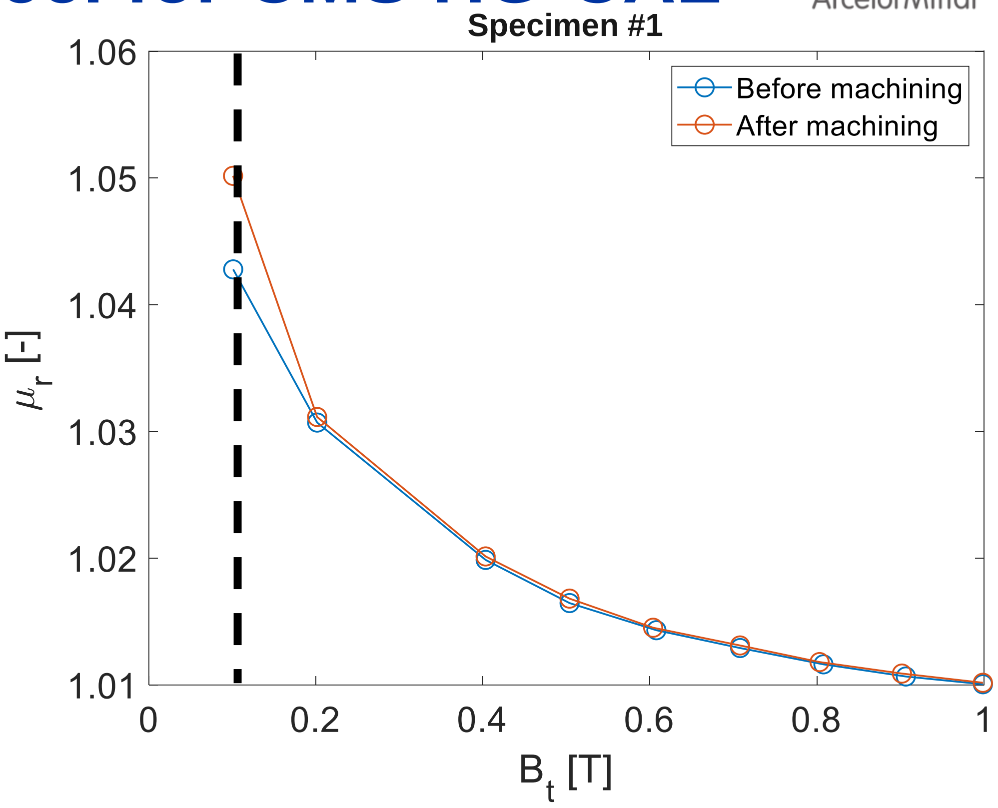


Inverse problem algorithm

Case study: a low permeability steel for CMS HG-CAL

ArcelorMittal Industeel





Foerster Magnetoscop 1.069

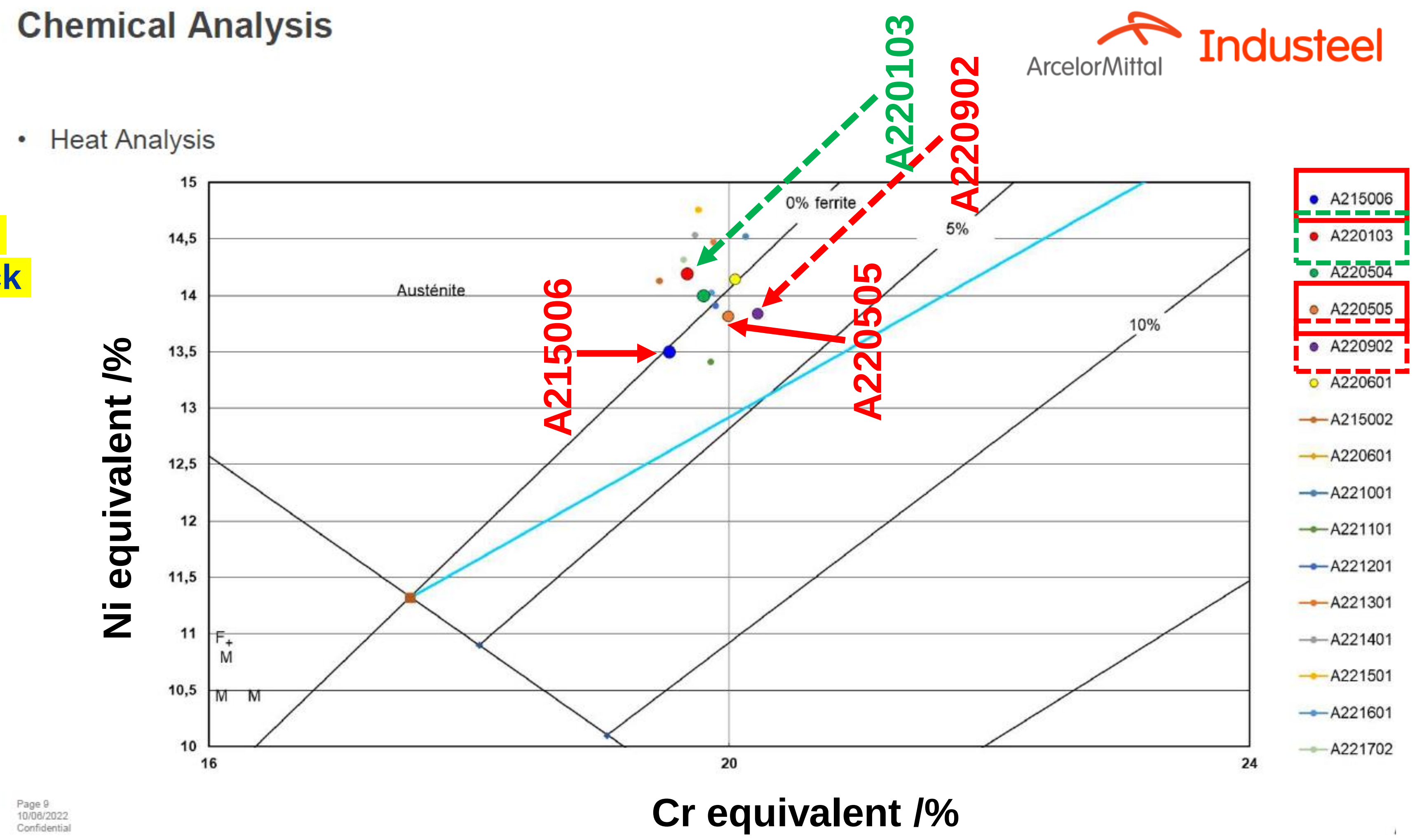
- **Specimen #1**: **1.0495** **before machining, 1.0519 after machining**
- **Specimen #2**: **1.0275**

SSM

- **Specimen #1** at 0.1 T: **1.04279** **before machining, 1.05017 after machining**
- **Specimen #2** at 0.1 T, **1.02319**

Case study: a low permeability steel for CMS HG-CAL

- The **origin of higher permeability of some plates can be traced back to the respective heats** and their position in the solidification diagram



Non-magnetic materials, phase transformations and measurements

Designation: A342/A342M – 14

Standard Test Methods for Permeability of Weakly Magnetic Materials[1]

This standard is issued under the fixed designation A342/A342M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1.2 The test methods covered are as follows:

1.2.1 *Test Method 1—Fluxmetric Method* is suitable for materials with permeabilities between 1.0 and 4.0. This method permits the user to select the magnetic field strength at which the permeability is to be measured.

1.2.2 *Test Method 2—Permeability of Paramagnetic Materials* has been eliminated as an acceptable method of test.

1.2.3 *Test Method 3—Low Mu Permeability Indicator* is suitable for measuring the permeability of a material as "less than" or "greater than" that of calibrated standard inserts with permeability between 1.01 and 6.0, as designated for use in a Low-Mu Permeability Indicator.[3] In this method, a small volume of specimen is subjected to a local magnetic field that varies in magnitude and direction, so it is not possible to specify the magnetic field strength at which the measurement is made.

1.2.4 *Test Method 4—Flux Distortion* is suitable for materials with permeability between 1.0 and 2.0. In this method, a small volume of specimen is subjected to a local magnetic field that varies in magnitude and direction, so it is not possible to specify the magnetic field strength at which the measurement is made.[4]

1.2.5 *Test Method 5—Vibrating Sample Magnetometry* is suitable for materials with permeability between 1.0 and 4.0. This test method permits the user to select the magnetic field strength at which the permeability is to be measured.

1.3 Materials typically tested by these methods such as austenitic stainless steels may be weakly ferromagnetic. That is, the magnetic permeability is dependent on the magnetic field strength. As a consequence, the results obtained using the different methods may not closely agree with each other. When using Methods 1 and 5, it is imperative to specify the magnetic field strength or range of magnetic field strengths at which the permeabilities have been determined.

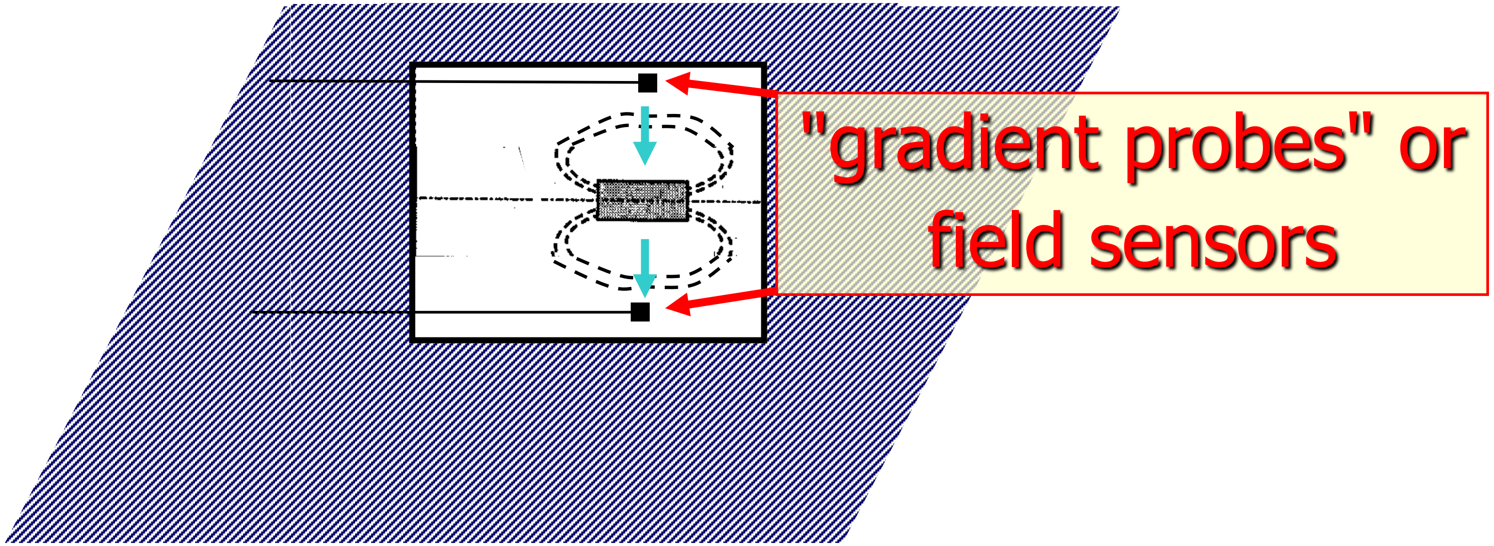
Non-magnetic materials, phase transformations and measurements

Courtesy of Foerster, MAGNETOSCOP® 1.069

- Measurement of material permeabilities
- Materials to be measured should be thicker than 8 mm
- Measurements of materials thinner than 8 mm by stacking two pieces
- Air gap between two pieces as small as possible
- Flat area not less than 20 mm in diameter
- Radius of curvature not be less than 40 mm
- Otherwise permeability less than actual value

Available in EN-MME-MM and TE-MSC

Non-magnetic materials, phase transformations and measurements

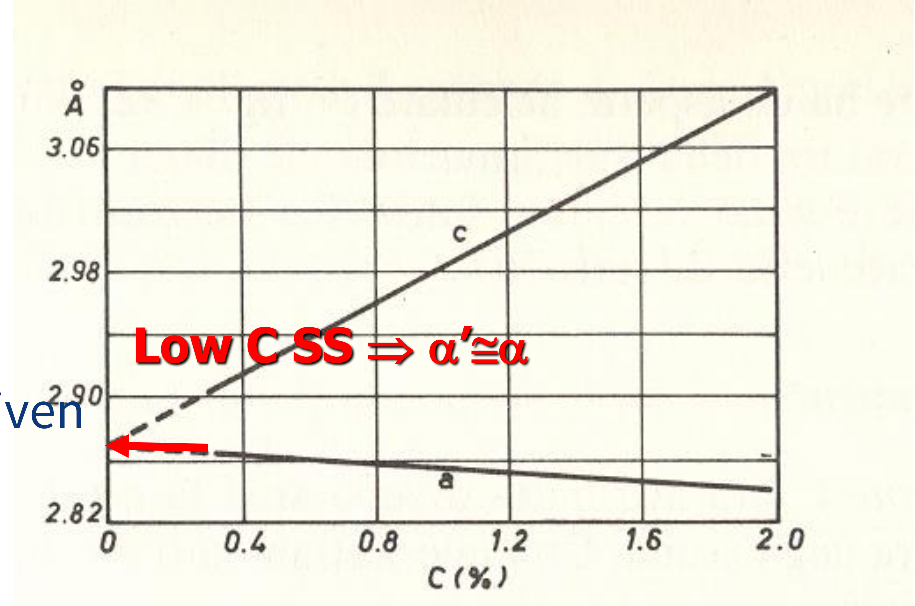


- "Based on a cylindrical permanent magnet
- A gradient probe is placed on either side of the cylindrical magnet in the plane perpendicular to the cylinder axis at the center of the permanent magnet
- If the cylindrical magnet is placed on a material whose permeability is greater than 1, there is a minute displacement of the magnetic zero of the cylindrical magnet towards the material on which the magnet has been placed
- In the lower permeability ranges this displacement is a measure of the permeability of the material"

Non-magnetic materials, phase transformations and measurements

Martensitic transformation have two forms:

- $\gamma \Rightarrow \alpha'$, b.c.c., relevant for magnetic purposes
- occurs spontaneously on cooling and/or is strain induced under a given temperature
- cause of loss of non-magnetism in austenitic stainless steels



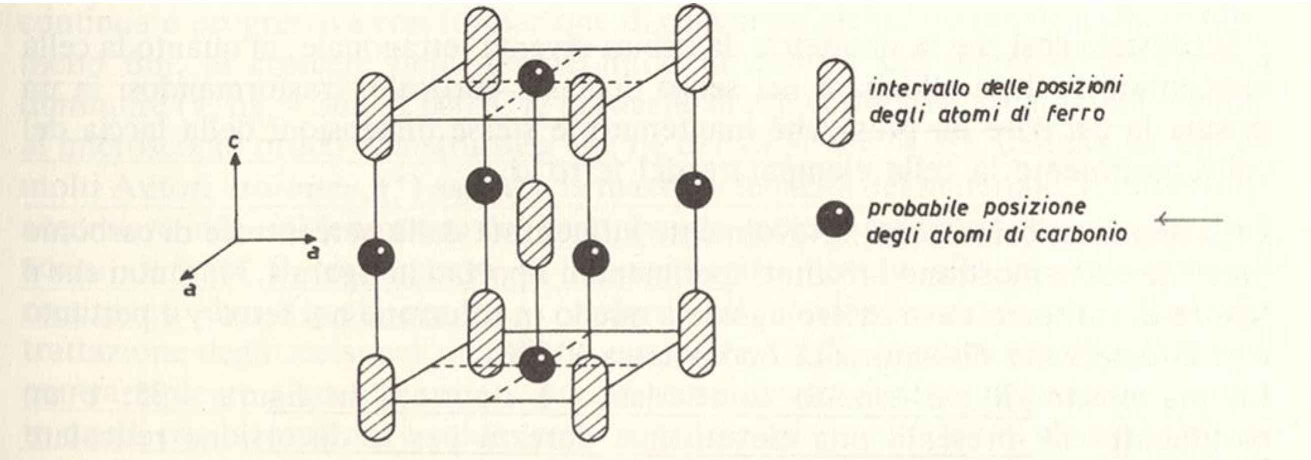


Fig. 4.33 *Schematizzazione del reticolo tetragonale della martensite: la forma allungata della posizione degli atomi di ferro sta ad indicare che la distanza reticolare degli stessi, relativamente all'asse c, può variare* (da H. Lipson).

Non-magnetic materials, phase transformations and measurements

Table 9.2 Temperature equivalents for calculation of stability parameters of austenitic steels.

Investigator (Year)	Base	Cr	Ni	Mn	Si	C	N	Mo	Other	Comments, Composition Range (wt.%)
f.c.c.→b.c.c. (T_{ms}), cooling[a]										
Eichelman, Hull (1953)	1									…: 10–18Cr, 6–12 Ni, …Mn, 0.3–26Si, 0.004–…, 0.01–0.06N
Monkman, Cuff, Grant (1957)	1455	−36.7	−56.7			−1460	−1460			49 alloys: 11–19Cr, 5–13Ni,
Hammond (1963)	1105	−29	−39							
Andrews (1965)	273	−12.1	−17.7	−3…						
Hull (1973)	1755	−47	−59	−5						0–0.15N, 0–6Mo, Co, 0–2Ti
f.c.c.→b.c.c. (T_{md}), deformation										
Angel (1954)										…nsion, 50% α′
Hull (1973)	1…									…mpression, 60 alloys: 12–24Cr, 0–22Ni, 0–20Mn, 0–4Si, 0–0.1C, 0–0.15N, 0–6Mo, Co
Williams, Williams, Capellaro (1976)	686	−6	−25	−16	+21	−222	−222	−11		45% compression, 2.5% α′, 25 alloys: 12–25Cr, 9–20Ni, 1–2Mn, 0.1–0.6Si, 0.04–0.25C, 0.01–0.1N, 0.6–2.8Mo

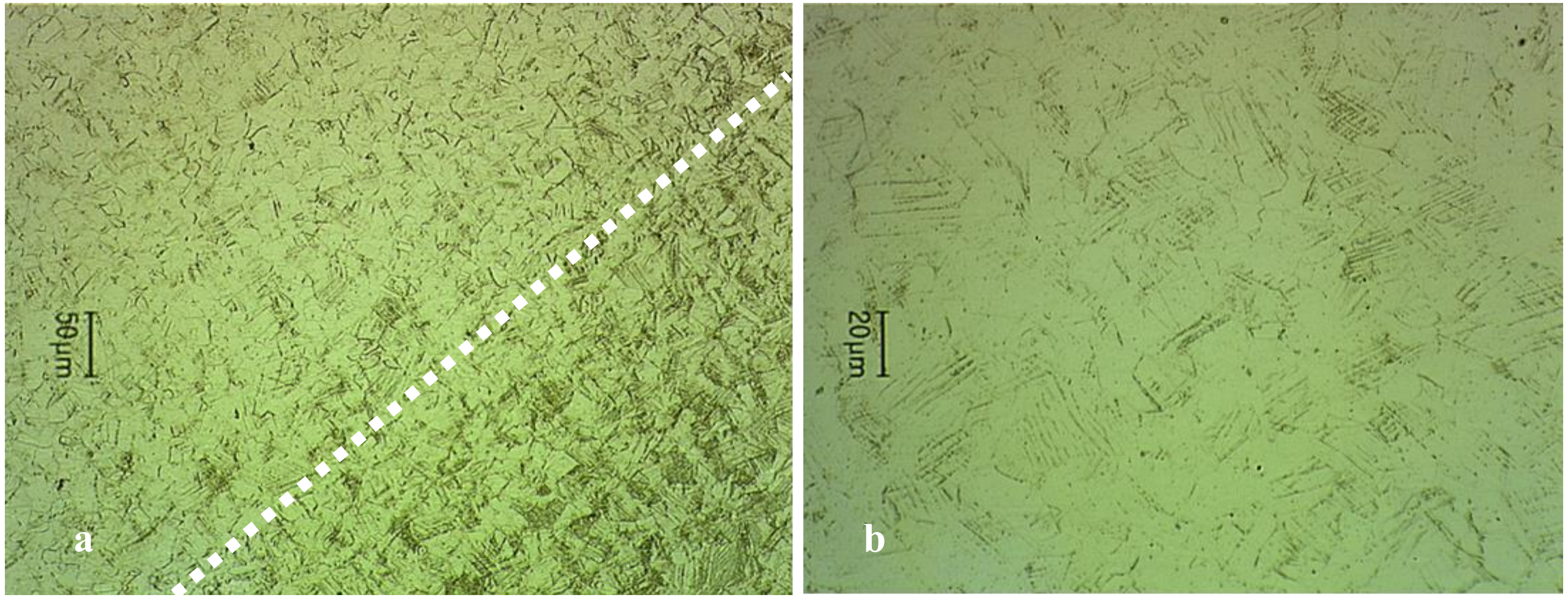
T_{ms}, temperature of spontaneous $\gamma \Rightarrow \alpha'$ martensitic transformation

Transformation (T_{ms}, T_{md}, calculated):

- General purpose 304L (1.4307, X2CrNi18-9) ⇒ T_{ms} = 280 K, T_{md} = 346 K
- High alloy 304L (1.4306, X2CrNi19-11) ⇒ T_{ms} = 140 K, T_{md} = 320 K
- Prototype HG-CAL 304L (as above) ⇒ T_{ms} = 76 K, T_{md} = 305 K
- CERN store 316LN (1.4429, X2CrNiMoN17-13-3) ⇒ T_{ms} = n.a., T_{md} = 240 K
- Beam screen P506 grade ⇒ T_{ms} = n.a., T_{md} = 36 K

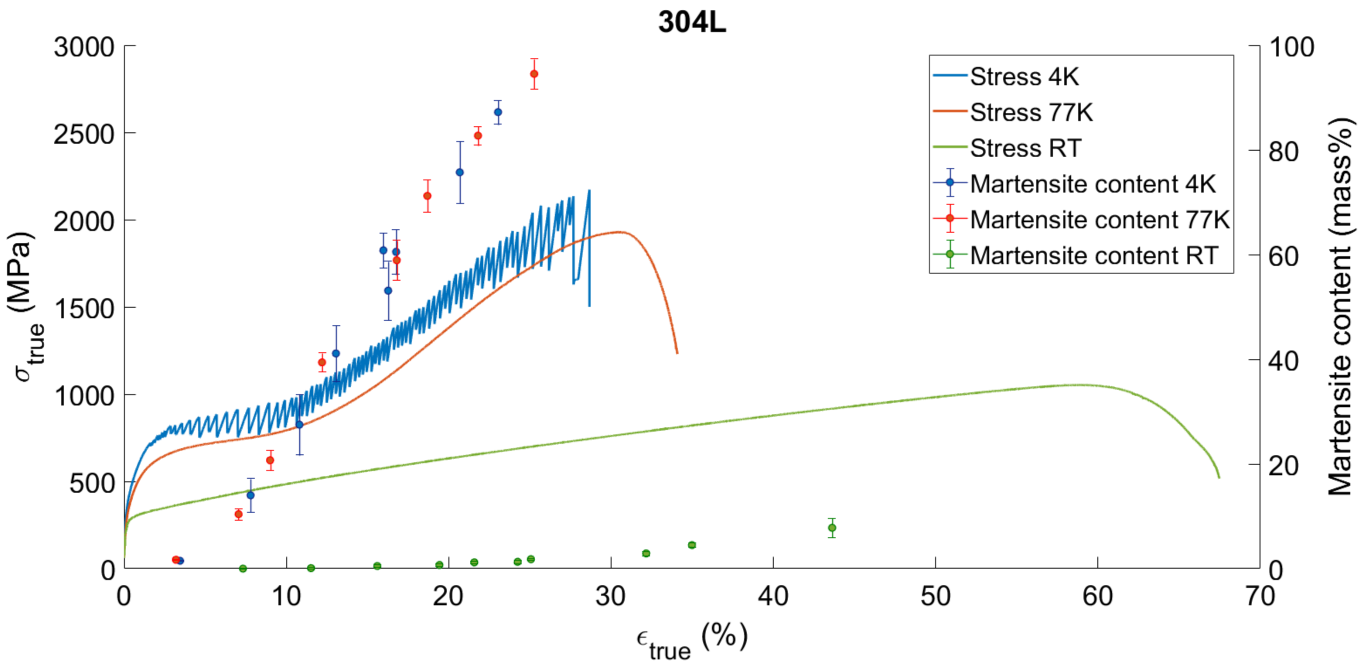
T_{md}, temperature of strain induced $\gamma \Rightarrow \alpha'$ martensitic transformation

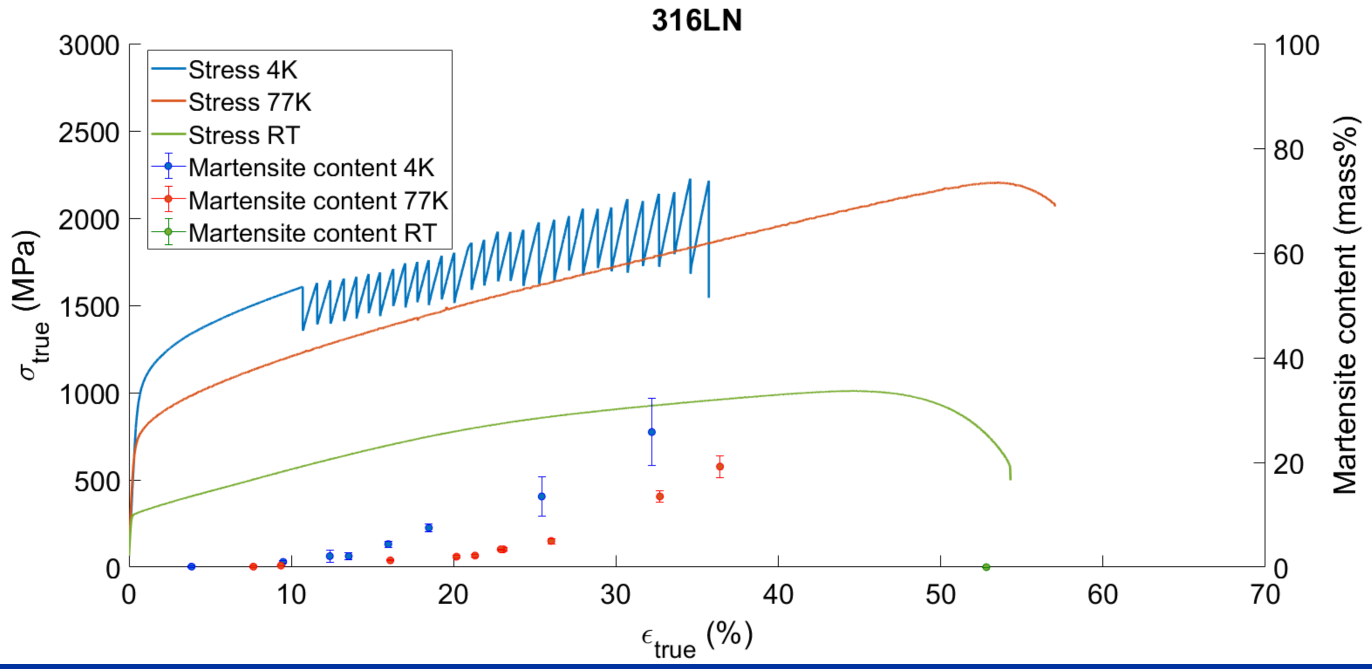
Non-magnetic materials, phase transformations and measurements



Partially transformed austenite of an AISI 316L austenitic stainless steel sample strained 6.5% at 4.2 K. Martensite is concentrated in bands (under the white boundary in Fig. a), developing during tensile deformation. A detail of the austenite-martensite microstructure is shown in Fig. b (see also C. GARION, S. SGOBBA, B. SKOCZEN, Constitutive modelling and identification of parameters of the plastic strain-induced martensitic transformation in 316L stainless steel at cryogenic temperatures, International Journal of Plasticity, 22 (2006) 1234-1264)

Non-magnetic materials, phase transformations and measurements





Non-magnetic materials, phase transformations and measurements

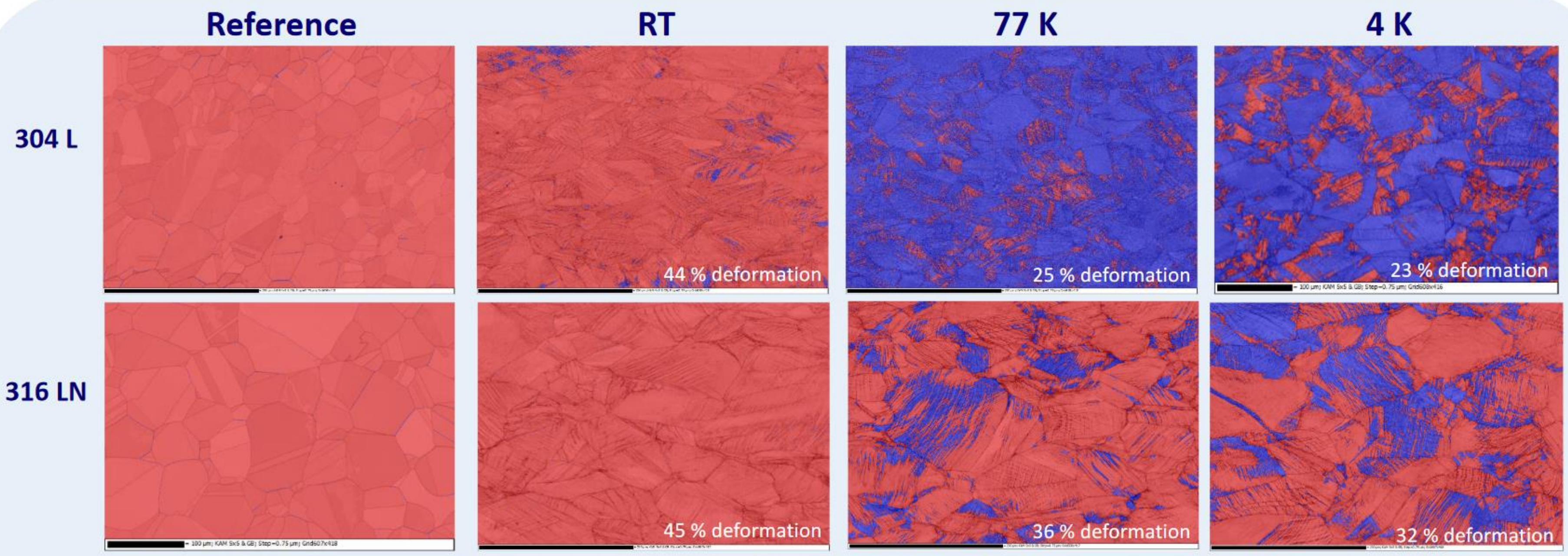


Figure 2 - EBSD phase map and band contrast map on 304 L and 316 LN samples at different temperatures. Colour code: martensite (Fe BCC) appears in blue, while the austenite (Fe FCC) is shown in red

Quantitative assessment through EBSD techniques associated to SEM

Flow and fracture of austenitic stainless steels at cryogenic temperatures, P. Fernández-Pisón, J.A. Rodríguez-Martínez, E. García-Tabarés, I. Avilés-Santillana, S. Sgobba (Dec, 2021), Engineering Fracture Mechanics 258 (2021) 108042, https://doi.org/10.1016/j.engfracmech.2021.108042

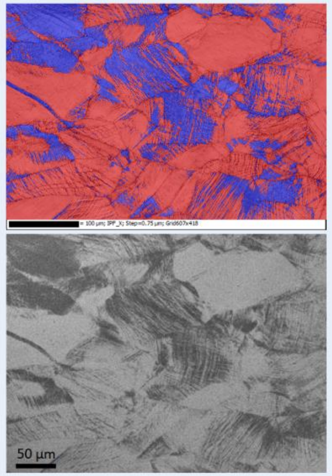
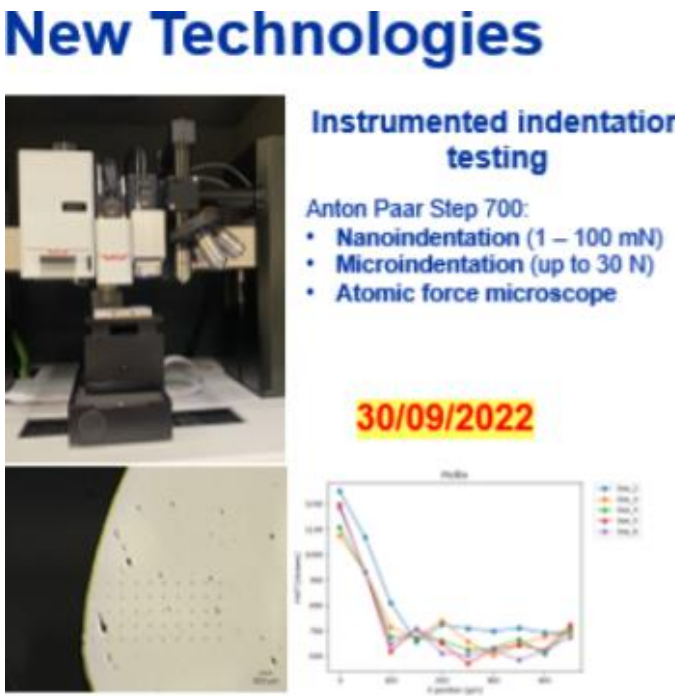


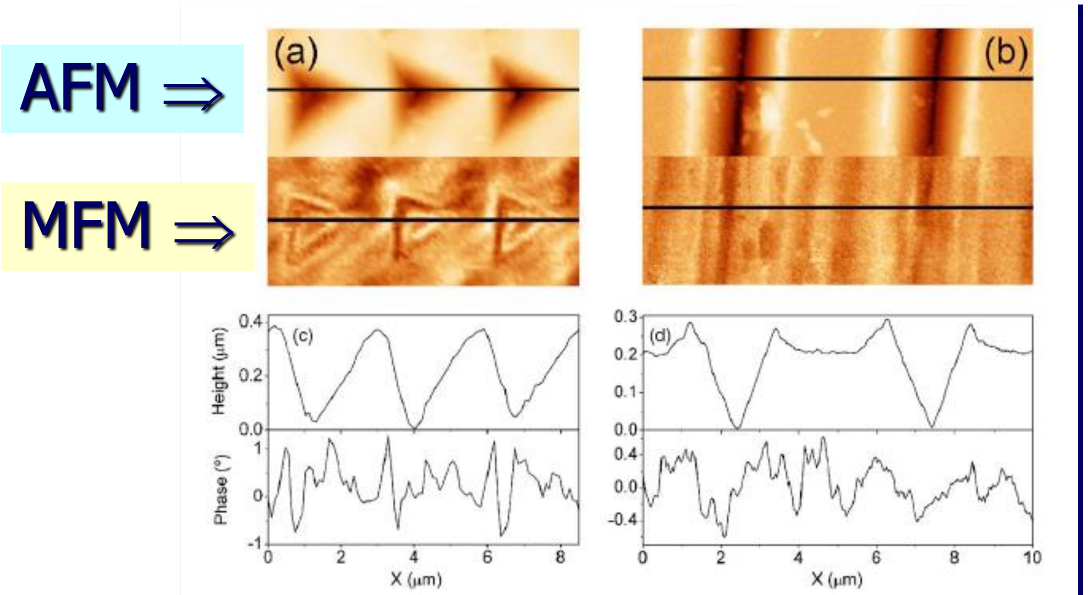
Figure 3 - Correlation between EBSD map and optical microscope image for SS 316 LN @ 4K, 32% deformation

Non-magnetic materials, phase transformations and measurements

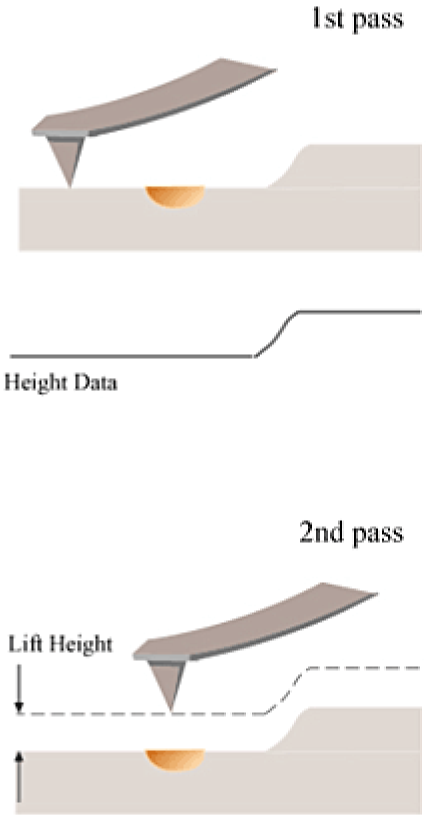


Now available in EN-MME-MM!

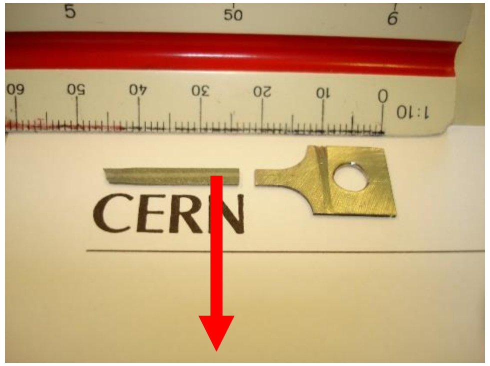
Commercial AISI 316 austenitic stainless steel, annealed at 1400 K

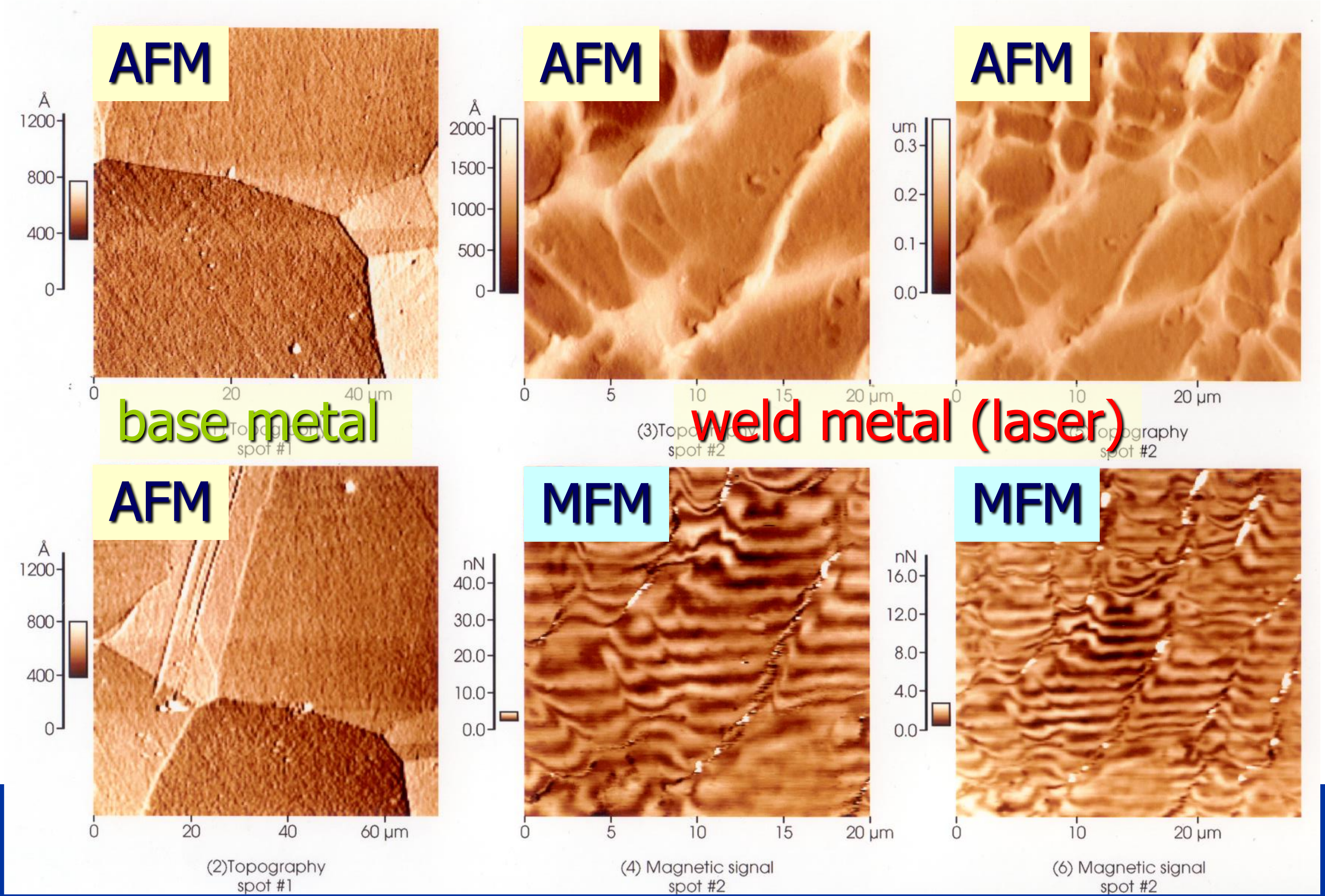


J. Sort et al., Applied Physics Letters **89** (2006) 032509



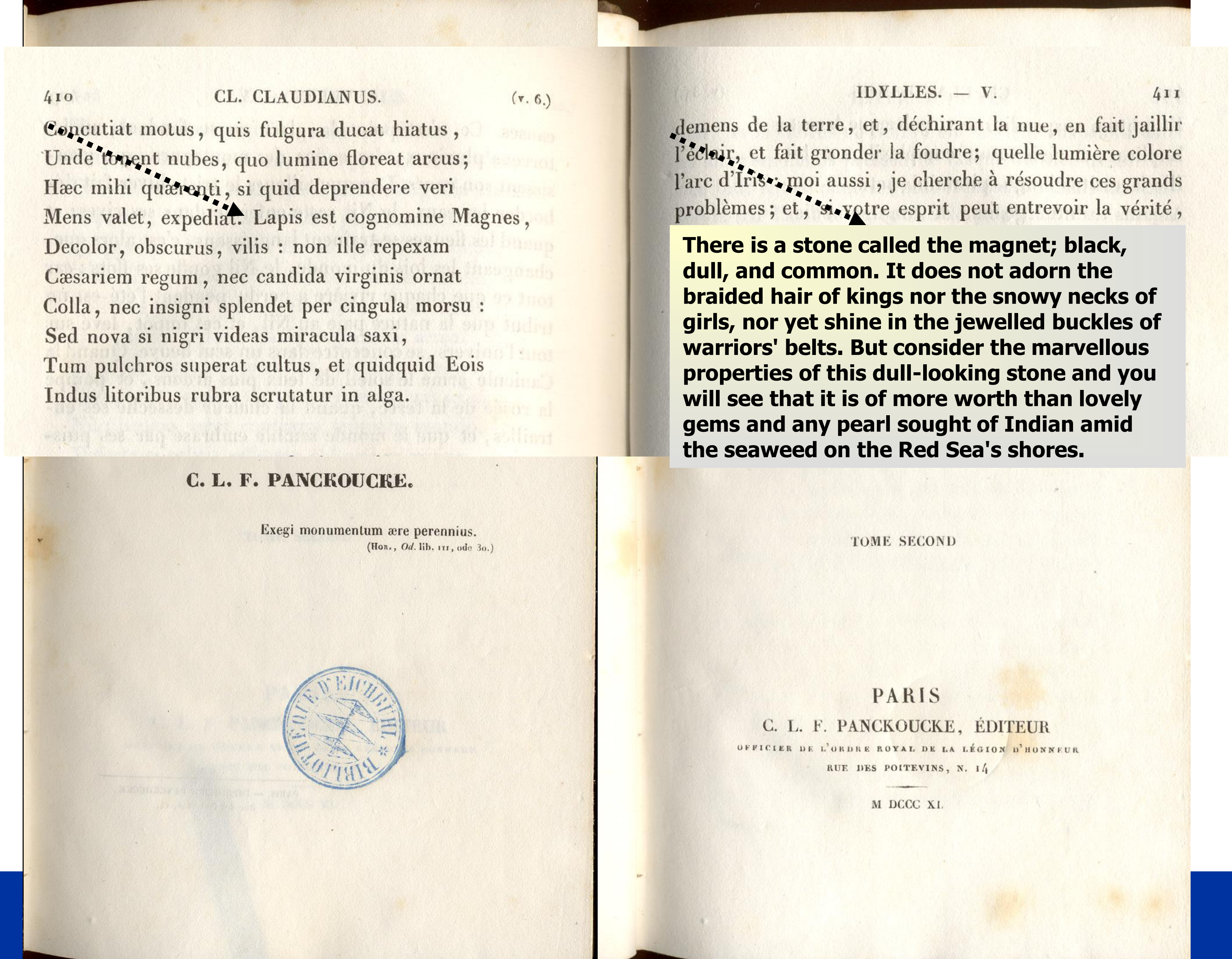
Non-magnetic materials, phase transformations and measurements





6. Conclusions

- Materials for an accelerator or fusion magnet part is not a mere "chemical composition" or a designation
  - specification
  - steelmaking
  - definition and extent of the controls
  - certification
  - quantity
  - price
- Application of extensive “state of the art” NDT techniques
  - stainless steels for vacuum, cryogenic and/or structural applications 100 % examined during production and at reception
- Low T and/or non-magnetism of components require special care and extensive cross check by advanced testing
- Irreprocheable production route, starting from steelmaking
- Advanced grades, even if standardized, imply extensive prior R&D. However, several grades already qualified for cryogenic structural applications



Concutiat motus, quis fulgura ducat hiatus,
Unde tonent nubes, quo lumine floreat arcus;
Hæc mihi quærenti, si quid deprendere veri
Mens valet, expediat. Lapis est cognomine Magnes,
Decolor, obscurus, vilis : non ille repexam
Cæsariem regum, nec candida virginis ornat
Colla, nec insigni splendet per cingula morsu :
Sed nova si nigri videas miracula saxi,
Tum pulchros superat cultus, et quidquid Eois
Indus litoribus rubra scrutatur in alga.

demens de la terre, et, déchirant la nue, en fait jaillir l'éclair, et fait gronder la foudre; quelle lumière colore l'arc d'Iris : moi aussi, je cherche à résoudre ces grands problèmes; et, si votre esprit peut entrevoir la vérité,

There is a stone called the magnet; black, dull, and common. It does not adorn the braided hair of kings nor the snowy necks of girls, nor yet shine in the jewelled buckles of warriors' belts. But consider the marvellous properties of this dull-looking stone and you will see that it is of more worth than lovely gems and any pearl sought of Indian amid the seaweed on the Red Sea's shores.

C. L. F. PANCKOUCKE.

Exegi monumentum ære perennius.
(Hor., *Od.* lib. III, ode 30.)

TOME SECOND

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OFFICIER DE L'ORDRE ROYAL DE LA LÉGION D'HONNEUR
RUE DES POITEVINS, N. 14
M DCCC XL

Spare slides

Case study: a low permeability steel for CMS HG-CAL

Plate	Averaging method	Localised measurement (0.1 T)	Volumetric measurement (0.1 T)
281142T – 120 mm (original thickness)	**Layers in thickness, including rolled faces**	**1.0495**	
	Mid thickness x 3 and rolled faces	*1.0522*	**1.04279**
	Mid thickness x 1 and rolled faces	*1.0306*	
281142T – 100 mm (machined down to)	**Layers in thickness, including rolled faces**	**1.0519**	
	Mid thickness x 3 and rolled faces	*1.0545*	**1.05017**
	Mid thickness x 1 and rolled faces	*1.0343*	
281146 – 60 mm	**Layers in thickness, including rolled faces**	**1.0275**	
	Mid thickness x 3 and rolled faces	*1.0508*	**1.02319**
	Mid thickness x 1 and rolled faces	*1.0343*	

ArcelorMittal Industeel

Case study: a low permeability steel for CMS HG-CAL

Two heats affected by ferrite precipitation resulting in 3:2 average μ_r > 1.05 on some plates

Plate n°	Heat n°	Thickness / mm	Average permeability 3:2	Average permeability 1:2
293526-11	A215006	60	1.065	1.040
293525-11	A215006	60	1.052	1.032
293525-21	A215006	60	1.044	1.027
293526-21	A215006	60	1.060	1.037
281146.11	A220902	60	1.038	1.025
281148.11	A220902	60	1.029	1.019
287355.11	A220103	80	1.006	1.008
287354.11	A220103	80	1.009	1.007
281088-11	A220505	80	1.088	1.057
280472.11	A215006	80	1.036	1.022
280470.11	A215006	80	1.021	1.014

A215006

A220505

A215006

ArcelorMittal Industeel

Case study: a low permeability steel for CMS HG-CAL

ArcelorMittal Industeel

Plate n°	Heat n°	Thickness / mm	Average permeability 3:2	Average permeability 1:2
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287354.11	A220103	80	1.009	1.007
281088-11	A220505	80	1.088	1.057
280472.11	A215006	80	1.036	1.022
280470.11	A215006	80	1.021	1.014

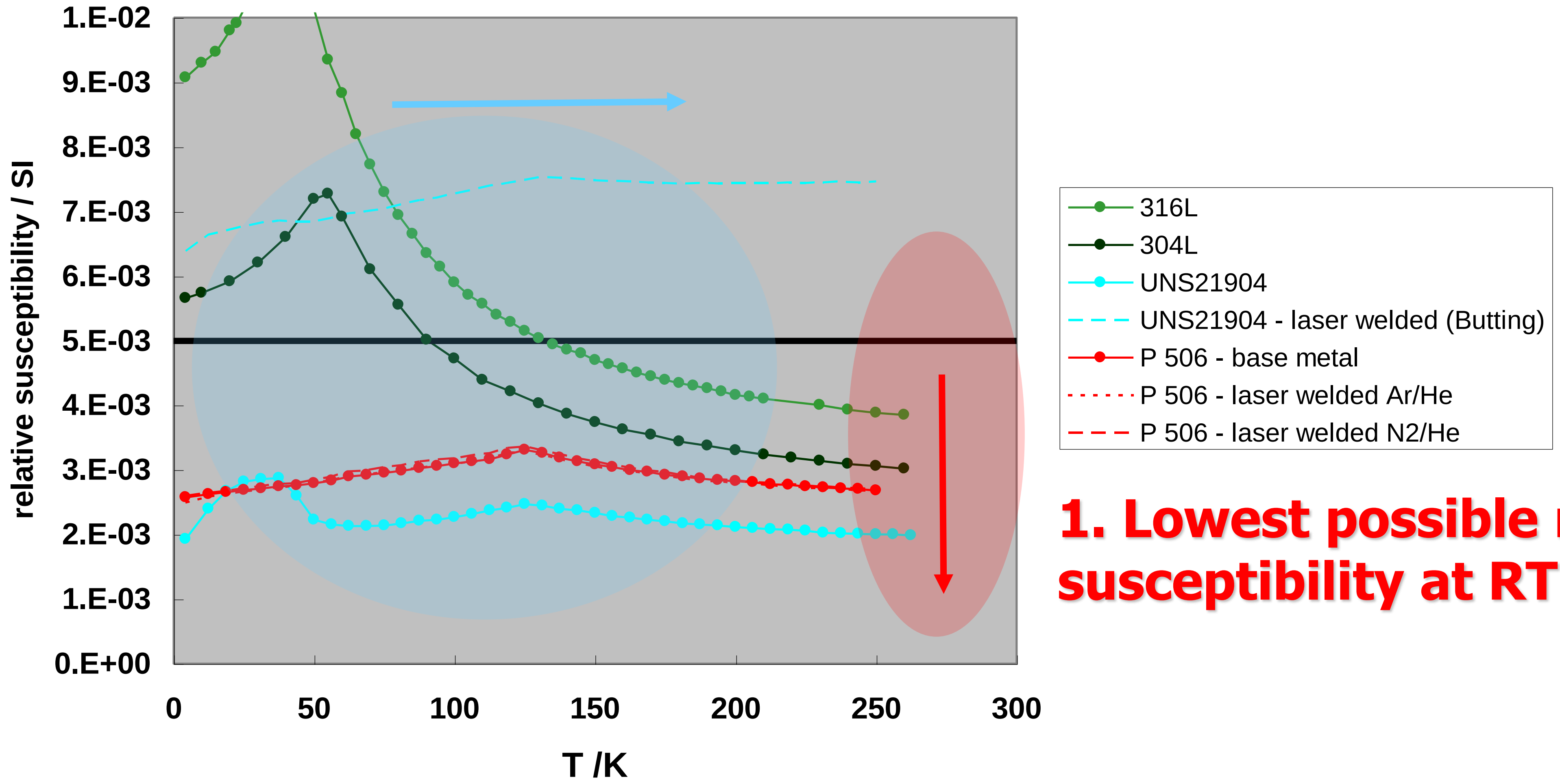
A220103
Low μ_r heat

Materials for magnets: austenitic stainless steels

Temperature [K]	direction	$\sigma_{y0.2}$ [MPa]	σ_r [MPa]	ε_r [%]
293	Long.	450 ± 10	835 ± 20	61 ± 3
	Transv.	440 ± 10	825 ± 5	45 ± 4
77	Long.	1180 ± 10	1760 ± 20	57 ± 4
	Transv.	1120 ± 50	1715 ± 100	45 ± 3
4.2	Long.	1620 ± 50	2115 ± 60	18 ± 3
	Transv.	1700 ± 100	2105 ± 90	15 ± 4

P506: remarkable combination of strength, ductility and impact toughness at 4.2 K

Materials for magnets: austenitic stainless steels



1. Lowest possible magnetic susceptibility at RT

2. Highest possible temperature of antiferromagnetic transition

3. Total absence of δ-ferrite in parent metal and welds ⇒ high purity of the parent metal

Materials for magnets: austenitic stainless steels

P. Libeyre et al., "*Addressing the Technical Challenges for the Construction of the ITER Central Solenoid*", IEEE Trans. Appl. Superconductivity, Vol. 22, (2012), p. 4201104

Tie plates, LKB and upper structures:
FXM-19 (Nitronic®50)

Yield strength required at RT when using JK2LB for the jackets: 230 MPa
→ F316LN excluded (205 MPa)
→ FXM-19 (Nitronic®50) selected (345 MPa)

- Initially considered both **forged or welded solution**
- Steelmaking process → ESR or VAR as needed, 3D forging
- Microinclusion cleanliness → As per ASTM E 45 method D ≤ 0.5 (A and C), ≤ 1.0 (B and D)
- Macroinclusions not permitted → ESR generally applied to meet this and other requirements
- Fineness of microstructure → grain size number ≥ 3 as per ASTM E112
- Homogeneity of microstructure → grain size within the range of ± 1 number
- **Limited ferrite content → less than number 1.0**
- **Limited magnetic permeability → ≤ 1.03**
- Internal soundness → 100 % UT
- Mechanical strength and fracture toughness specified, including at cryogenics →

S.A.E. Langeslag et al., "*Extensive Characterisation of Advanced Manufacturing Solutions for the ITER Central Solenoid Pre-compression System*," Fusion Eng. Des. (2015), https://doi.org/10.1016/j.fusengdes.2015.06.007

R. Walsh et al., "*Welded tie plate feasibility study for ITER central solenoid structure*", Adv. Cryo. Eng, AIP Conference Proceedings 1574, 16 (2014); https://doi.org/10.1063/1.4860598

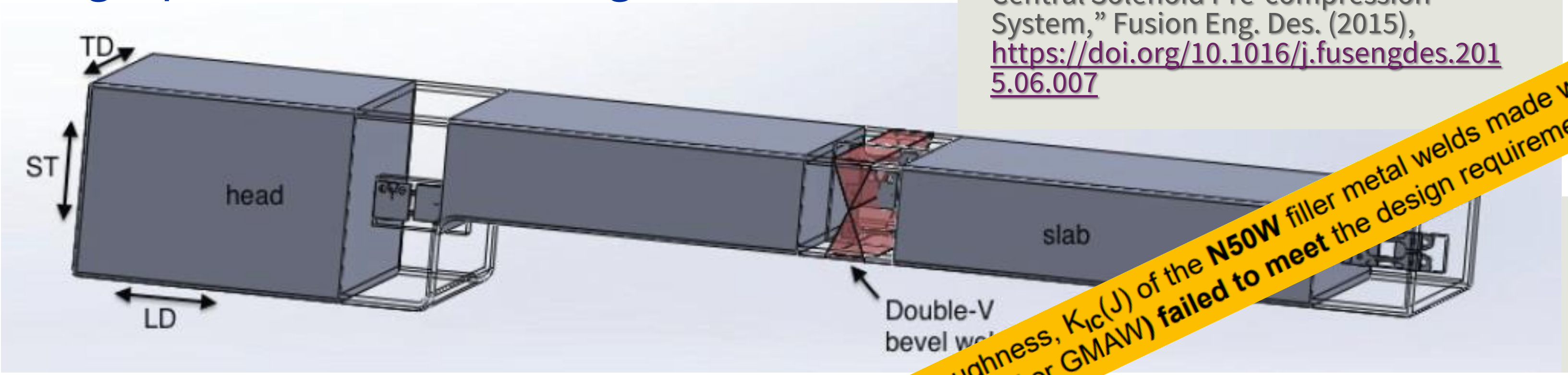
Materials for magnets: austenitic stainless steels

Requirements:

- Very high strength and toughness at 4 K: Rp_{02} > 1200 MPa; Rm > 1600 MPa; K_{IC} > 130 MPa √m
- Fatigue resistance at cryogenic temperature
- Larger thermal contraction than central solenoid jackets (JK2LB) for an effective pre-compression at 4 K

Single piece welded and forged solution

S.A.E. Langeslag et al., "Extensive Characterisation of Advanced Manufacturing Solutions for the ITER Central Solenoid Pre-compression System," Fusion Eng. Des. (2015), https://doi.org/10.1016/j.fusengdes.2015.06.007

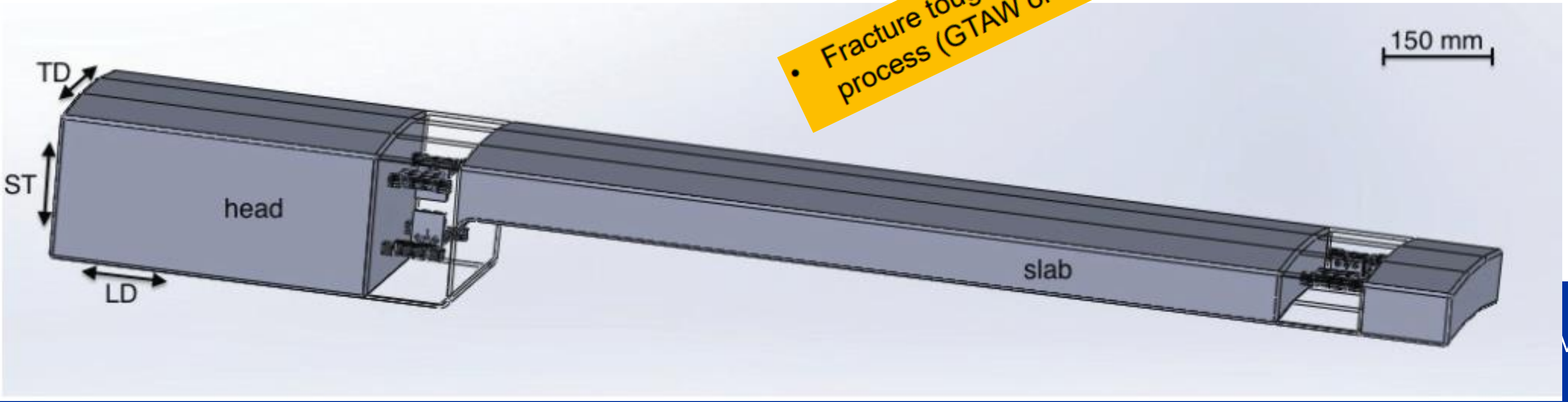


Head- and slab-forgings, joined together via a Gas Metal Arc Welding (GMAW) process.

- The cryogenic mechanical properties of weld did not fulfil the requirements

- Fracture toughness, $K_{IC}(J)$ of the **N50W** filler metal welds made with either process (GTAW or GMAW) **failed to meet** the design requirements.

R. Walsh et al., "*Welded tie plate feasibility study for ITER central solenoid structure*", Adv. Cryo. Eng, AIP Conference Proceedings 1574, 16 (2014); https://doi.org/10.1063/1.4860598

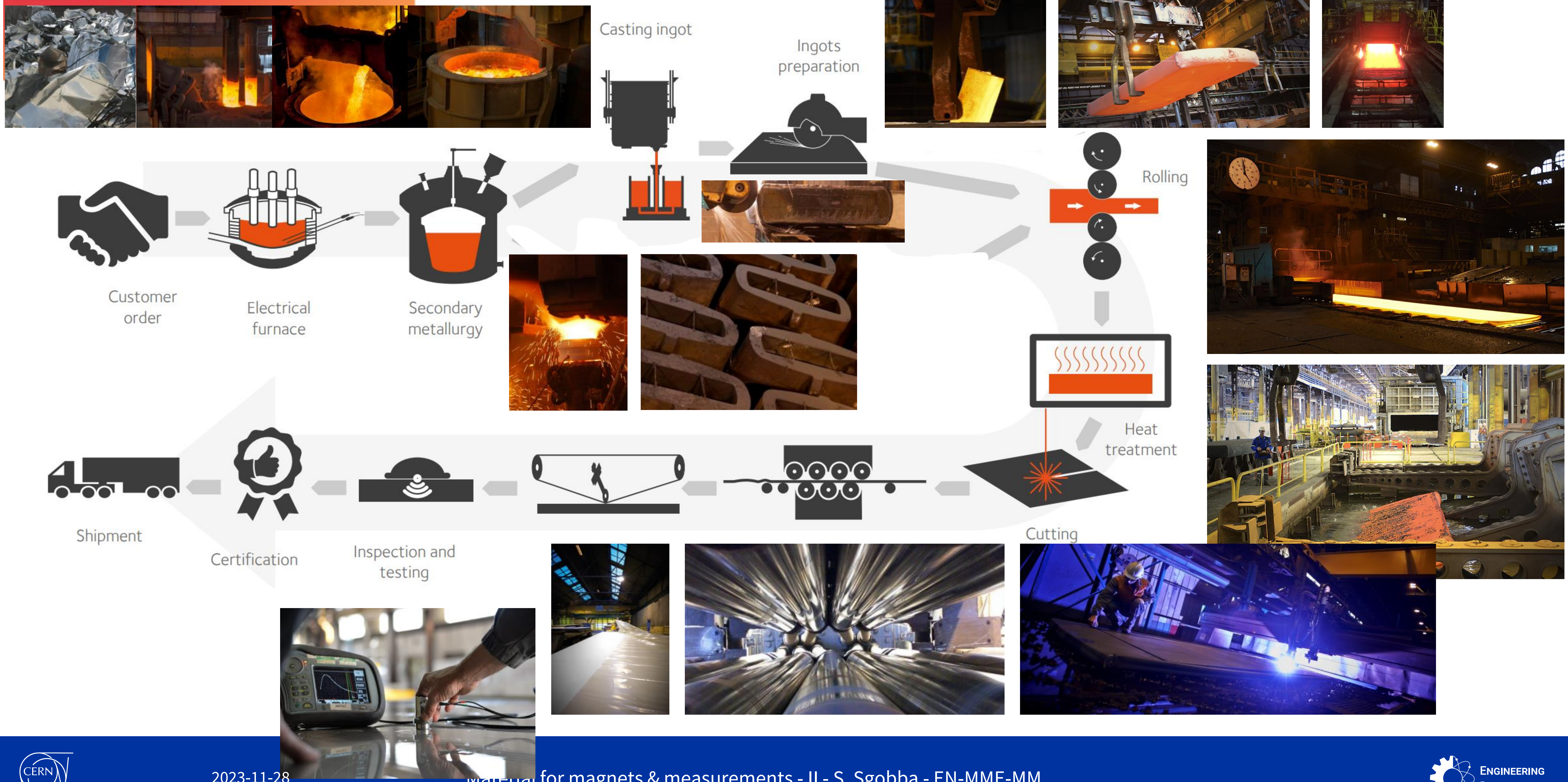


Produced by applying successive forging steps, followed by a final machining operation.

- Higher mechanical properties, including cryogenic fracture toughness and lower

Our process

Courtesy Dr. N. Pauze, ArcelorMittal Industeel



Non-magnetic materials, phase transformations and measurements

All coefficient are negative:

- good rule: "the more alloying elements one uses (and can afford!), the more stable the austenite will be"
- 304L is the least stable among the alloys used at CERN.
- **1.4306** generally specified by CERN and preferred to **1.4307** (general purpose)
- total stability requires a specific alloy selection or design, see the (HL-) LHC beam screen example

Transformation (T_{ms}, T_{md}, calculated):

- General purpose 304L (1.4307, X2CrNi18-9) ⇒ **T_{ms} = 280 K, T_{md} = 346 K**
- High alloy 304L (1.4306, X2CrNi19-11) ⇒ **T_{ms} = 140 K, T_{md} = 320 K**
- Prototype HG-CAL 304L (as above) ⇒ **T_{ms} = 76 K, T_{md} = 305 K**
- CERN store 316LN (1.4429, X2CrNiMoN17-13-3) ⇒ **T_{ms} = n.a., T_{md} = 240 K**
- Beam screen P506 grade ⇒ **T_{ms} = n.a., T_{md} = 36 K**